2012 International Workshop on EUV and Soft X-Ray Sources

October 8-11, 2012

Dublin ▪ Ireland

Workshop Abstracts

EUV Litho, Inc.

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2012 International Workshop on EUV and Soft X-ray Sources

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Welcome

Dear Colleagues;

I will like to welcome you to the 2012 International Workshop on EUV and Soft X-Ray Sources in Dublin, Ireland.

3rd annual source workshop is now the largest annual gathering of EUV and XUV source experts. This workshop will provide a forum for researchers in the EUV and soft X-ray areas to present their work and discuss potential applications of their technology. I expect that researchers as well as the end-users of EUV and soft X-ray sources will find this workshop valuable. The workshop proceedings will be published online.

The EUV Source Workshop is organized by University College Dublin (UCD) and EUV Litho, Inc. This workshop has been made possible by the support of workshop sponsors, technical working group (TWG), workshop support staff, session chairs and presenters. I would like to thank them for their contributions and making this workshop a success. I look forward to your participation in the workshop.

Best Regards

Vivek Bakshi
Organizing Chair, 2012 International Workshop on EUV and Soft X-Ray Sources

Source Technical Working Group (TWG)

Reza Abhari (ETH Zurich)
Jinho Ahn (Hanyang University)
Peter Anastasi (Silson)
Sasa Bajt (DESY)
Vadim Banine (ASML)
Klaus Bergmann (XTREME / ILT-Fraunhofer)
Davide Bleiner (University of Bern)
Vladimir Borisov (Triniti)
John Costello (DCU)
Samir Ellwi (Adlyte)
Akira Endo (Waseda University)
Henryk Fiedorowicz (Military University of Technology, Poland)
Torsten Feigl (IOF-Fraunhofer)
Francesco Flora (ENEA)
Debbie Gustafson (Energetiq)
Ahmed Hassanein (Purdue)
Takeshi Higashiguchi (Utsunomia University)
Larissa Juschkin (Aachen University)
Hiroo Kinoshita (Hyogo University)
Chiew-seng Koay (IBM)
Konstantin Koshelev (ISAN)
Rainer Lebert (Bruker)
Peter Loosen (ILT-Fraunhofer)
Eric Louis (FOM)
James Lunney (Trinity College, Dublin)
John Madey (University of Hawaii)
Shunko Magoshi (EIDEC)
Alan Michette (King's College London)
Hakaru Mizoguchi (Gigaphoton)
Katsuhiko Murakami (Nikon)
Patrick Naulleau (LBNL)
Katsunobu Nishihara (Osaka University)
Fergal O'Reilly (UCD)
Gerry O'Sullivan (UCD)
Luca Ottaviano (University of L'Aquila)
Yuriy Platonov (RIT)
Martin Richardson (UCF)
Valentino Rigato (INFN-LNL)
Jorge Rocca (University of Colorado)
David Ruzic (University of Illinois)
Akira Sasaki (JAEA)
Leonid Shmaenok (PhysTex)
Menachem Shoval (Intel)
Emma Sokell (UCD)
Harun Solak (PSI)
Seichi Tagawa (Osaka University)
Mark Tillack (UC San Diego)
Andrei Yakunin (ASML)
Hironari Yamada (PPL)
Sergey Zakharov (EPPRA)
Vivek Bakshi (EUV Litho, Inc.) - Organizing Chair
Padraig Dunne (UCD) - Organizing Co-Chair

Workshop Agenda

Agenda Outline

Monday, October 8, 2012

Location: Newman House, Stephen's Green, Dublin

6:00 - 7:00 PM	Reception and Speaker Prep

Tuesday, October 9, 2012

Location: Clinton Auditorium, UCD Campus, Dublin

7:45 AM	Pickup at the Hotel (Stephen's Green and Burlington Hotel)
8:30 AM – 11:30 AM	Workshop Presentations
11:40 AM -12:40 PM	Lunch
12:40 PM – 5:30 PM	Workshop Presentations
5:30 PM – 6:30 PM	Poster Session and Reception
6:30 PM	Depart for Off-Site Dinner (Pickup at Clinton Auditorium)

Wednesday, October 10, 2012

Location: Clinton Auditorium
UCD Campus, Dublin

7:45 AM	Pickup at the Hotel (Stephen's Green and Burlington)
8:30 AM – 1:00 PM	Workshop Presentations
1:00 PM - 2:00 PM	Lunch
2:00 PM	Depart for tour of Trim Castle (Pickup at Clinton Auditorium)

Thursday, October 11, 2012

Location: Newman House, Stephen's Green, Dublin

Technical Working Group (TWG) Meeting

8:30 AM	Continental Breakfast
9:00 AM – 10:00 AM	TWG Meeting

WORKSHOP AGENDA

2012 International Workshop on EUV and Soft X-Ray Sources

October 8-11, 2012, Dublin, Ireland

Monday, October 8, 2012 (Newman House)

6:00 PM – 7:00 PM Reception and Registration

Tuesday, October 9, 2012 (Clinton Auditorium)

8:30 AM Session 1 : Welcome and Announcements

Introduction and Announcements (Intro-1)
Vivek Bakshi, EUV Litho, Inc., USA
Des Fitzgerald, VP, UCD

8:40 AM Session 2: Keynote-1

Session Chair: Vadim Banine (ASML)

High Repetition Rate Table-top Soft X-Ray Lasers (S1)
J. J. Rocca[1,2,3], B. Reagan [1,2], Y. Wang,[1,2] , D. Alessi, B. M. Luther[1,2], K. Wernsing[1,2], L. Yin [1,2] , M. A. Curtis [1,2], M. Berrill[1,2] , D. Martz [1,2] , V.N. Shlyaptsev[1,2] , S. Wang [1,2] , F. Furch [1,3], M. Woolston [1,2], D. Patel [1,2], C.S. Menoni [1,2]
[1] National Science Foundation ERC for Extreme Ultraviolet Science and Technology
[2] Electrical and Computer Engineering Department, Colorado State University, Fort Collins, CO 80523
[3] Physics Department, Colorado State University, Fort Collins, CO 80523

Extendibility of LPP EUV Source Technology in Higher Power (kW) and Shorter Wavelength (6.x nm) Operation (S2)
Akira Endo
Waseda University, Tokyo, Japan
HiLASE Project, Prague, Czech Republic

Awards and Announcements – Padraig Dunne (UCD)

Break 10:00 AM

10:20 AM Session 3: HVM EUV Sources

Session Chair: Katsuhiko Murakami (NIKON)

EUV Lithography: Today and Tomorrow? (S10) (Invited Paper)
Vadim Banine
ASML, The Netherlands

EUVL - A Reality in the Making
The Reality of Laser Assisted Discharge Plasma EUV Light Sources (S49)
(Invited Paper)
Jeroen Jonkers
XTREME technologies, GmbH, Steinbachstrasse 15, 52074 Aachen, Germany

New type of DPP source with liquid tin jets electrode - recent progress (S61)
V.Krivtsun *, O.Yakushev *, A.Vinohodov*, ** , V.Borisov** , V.Ivanov* and K.Koshelev*.
** RnD-ISAN / EUVLabs, ** TRINITI*

High Brightness, High-average Power Picosecond Thin Disc Laser Program to Specific Requirements from Short Wavelength Light Sources (S28)
Taisuke Miura, Michal Chyla, Martin Smrž, Patricie Severová, Ondřej Novák, Akira Endo, and Tomáš Mocek
HiLASE Project, Institute of Physics AS, CR, Na Slovance 2, 182 21 Prague 8, Czech Republic

Lunch 11:40 AM

12:40 PM Session 4: EUV Sources for Mask Metrology

Session Co-Chairs: Klaus Bergman (ILT-Fraunhofer) and Larissa Juschkin (RWTH – Aachen)

EUV Source For Metrology of EUV Masks *(Tentative title)* **(S51)** (Invited Paper)
Heiko Feldmann
Carl Zeiss, 73447 Oberkochen, Germany

Discharge based EUV Source for Metrology (S58) (Invited Paper)

Klaus Bergmann
Fraunhofer Institute for Laser Technology, Steinbachstr. Aachen, Germany

Electrodeless Z-Pinch™ EUV Source for Next Generation EUV Metrology (S36)
(Invited Paper)
Deborah Gustafson, Stephen F. Horne, Matthew M. Besen, Donald K. Smith, Matthew J. Partlow, Paul A. Blackborow
Energetiq Technology, Inc., 7 Constitution Way, Woburn, MA, USA 01801

Recent Progress on High Brightness Source Collector Module for EUV Mask Metrology (S31)
Paul Sheridan[1], Kenneth Fahy[1], Padraig Dunne[2], and Fergal O'Reilly[2]
[1]*NewLambda Technologies Ltd, Science Center North, Belfield, Dublin 4, Ireland*
[2] *UCD School of Physics, UCD, Stillorgan Rd, Dublin 4, Ireland*

Source Brightness Requirements for EUV Microscopes (S39)
(Invited Paper)
Larissa Juschkin[1], Fergal O'Reilly[2]
[1]*RWTH Aachen University, Experimental Physics of EUV, Steinbachstr. 15, 52074 Aachen, Germany*
and JARA - Fundamentals of Future Information Technology (FIT), 52425 Jülich, Germany
[2]*School of Physics, University College Dublin, Belfield, Dublin 4, Ireland*

Break 2:00 PM (20 Minutes)

2:20 PM Session 5: Modeling

Session Co-Chairs: Gerry O'Sullivan (UCD) and Sergey Sergey V. Zakharov (EPPRA)

Modeling and Optimization of Pre-conditioned LPP targets (S52) (Invited Paper)
K. N. Koshelev[1,2], V. V. Ivanov[1,2], V. G. Novikov[1,3], V. M. Krivtsun[1,2], A. S. Grushin[1,3] , V. Medvedev[4]
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[2]*Institute of Spectroscopy RAS, Troitsk, 142090 Russia*
[3]*Keldysh Institute of Applied Mathematics RAS, Moscow, 125047 Russia*
[4]*Dutch Institute for Fundamental Energy Research, Nieuwegein, The Netherlands*

Unresolved Transition Arrays and their role in EUV and Soft X-ray Source Development (S56)

Gerry O'Sullivan[1], John Costello[2], Thomas Cummins[1], Rebekah D'Arcy[1], Padraig Dunne[1], Akira Endo[3], Paddy Hayden[2], Takeshi Higashiguchi[4], Imam Kambali[1], Deirdre Kilbane[1], Bowen Li[1], Colm O'Gorman[1], Takamitsu Otsuka[4], Emma Sokell[1] and Noboru Yugami[4]
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[4]Department of Advanced Interdisciplinary Sciences, Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan.

Properties of High-intensity EUV & Soft-X Radiation Plasma Sources (S25) (Invited Paper)
Vasily S. Zakharov[1,2], Sergey V. Zakharov [1,2,3], Peter Choi[1]
[1]EPPRA sas, Villebon sur Yvette, France in collaboration with KIAM RAS, Moscow, Russia
[2]NRC Kurchatov Institute, Moscow, Russia
[3]JIHT RAS and SRC RF TRINITI, Moscow, Russia

4:00 PM Session 6: EUV/ BEUV/ XUV Optics

Session Co-Chairs: Eric Louis (DIFFER) and Yuriy Platonov (RIT)

Multilayers for 6.8 nm Wavelength (S50) (Invited Paper)
I.A. Makhotkin[1], E. Louis[1] ,E. Zoethout[1], R.W.E. van de Kruijs[1], Andrei M. Yakunin[2], Stephan Müllender[3] and F. Bijkerk[1,4]
[1] FOM Institute DIFFER - Dutch Institute for Fundamental Energy Research, Nieuwegein, the Netherlands
[2] ASML, Veldhoven, the Netherlands
[3] Carl Zeiss SMT GmbH, Oberkochen, Germany
[4] MESA+ Institute for Nanotechnology, University of Twente, Enschede, the Netherlands

New High Reflective Multilayer Designs for the EUV and Soft X-ray Range (S57) (Invited paper)
Marco Perske, Hagen Pauer, Tobias Fiedler, Sergiy Yulin, Viatcheslav Nesterenko, Mark Schürmann, Torsten Feigl, Norbert Kaiser
Fraunhofer-Institut für Angewandte Optik und Feinmechanik, Albert-Einstein-Str. 7, 07745 Jena, Germany

Optics for EUV/XUV/XR Sources and Laboratory Submicron Microscopy (S55) (Invited Paper)
Ladislav Pina[1], Veronika Pickova[1], Radka Havlikova[1], Hana Zakova[2], Alexandr Jancarek[1], Adolf Inneman[3], Martin Horvath[3], Jiri Marsik[3], Peter Oberta[3], Henryk Fiedorowicz[4], Andrzej Bartnik[4]
[1] Czech Technical University in Prague, Faculty of Nuclear Sciences and Phys. Engineering, 115 19 Prague 1, Czech Republic

[2]Czech Technical University in Prague, Faculty of Biomedical Engineering, 272 01 Kladno, Czech Republic
[3]Rigaku Innovative Technologies Europe, 142 21 Prague 4, Czech Republic
[4]Military University of Technology, Institute of Optoelectronics, 00-908 Warszawa 49, Poland

Corrosion-resistant, Triple-wavelength Mg/SiC Multilayer Coatings for the 25-80 nm Wavelength Region (S45) (Invited Paper)
Regina Soufli[1], Mónica Fernández-Perea[1], Jeff C. Robinson[1], Sherry L. Baker[1], Jennifer Alameda[1], Christopher C. Walton[1], Luis Rodríguez-De Marcos[2], Jose A. Méndez[2], Juan I. Larruquert[2], Eric M. Gullikson[3]
[1]Lawrence Livermore National Laboratory, Livermore, California, US
[2]Instituto de Óptica, Consejo Superior de Investigaciones Científicas, Madrid, Spain
[3]Lawrence Berkeley National Laboratory, Berkeley, California, US

Nanoscale Multilayer Membranes as Optical Elements for EUVL (S59)
Nikolay Chkhalo[1], Mikhail Drozdov[1], Evgeny Kluenkov[1], Aleksei Lopatin[1], Valerii Luchin[1], Nikolay Salashchenko[1], Nikolay Tsybin[1], Leonid Sjmaenok[2] ,Vadim Banine[3], Luigi Scaccabarozzi[3], Andrei Yakunin[3]
[1]Institute for Physics of Microstructures RAS,Ulyanova 46, 603155 Nizhniy, Novgorod, Russia
[2]PhysTeX, Jos Francotteweg 6b, 6291 GP Vaals, Netherlands
[3]ASML Netherlands, De Run 6501, 5504 DR Veldhoven, Netherlands

5:30 PM – 6:30 PM Session 7: Poster Session

7:00 PM Depart for Off-site Dinner (Royal Dublin Society)

End of Day 2

5:30 PM Session 7: Poster Session

Topic: HVM Sources

Next Generation of EUV Lithography: Challenges and Opportunities (S47)
Andrei M. Yakunin, Vadim Banine
ASML, Veldhoven, The Netherlands

Direct Diagnostics Concept for High Power CO_2 Laser at the LPP Focus Spot (S20)
Kazuyuki Sakaue, Yasufumi Yoshida, Ryo Sato, Masakazu Washio, Akira Endo
Research Institute for Science and Engineering, Waseda university, 3-4-1 Okubo, Shinjuku, Tokyo 169-855 Japan

Research of the CO_2 Laser MOPA System (S44)
Wang Xinbing[1*], Zuo DuLuo[1], Lu Peixiang[2]
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[2] *School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China*

2D PIC Modeling of the EUV Induced Hydrogen Plasma and Comparison to the Observed Carbon Etching Rate (S27)
D.I. Astakhov[1,3*], W.J. Goedheer[1], D.V. Lopaev[2], V.V. Ivanov[3], V.M. Krivtsun[3], O. Yakushev[3], K.N. Koshelev[3], and F. Bijkerk[1,4]
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Topic: EUV Sources for Mask Metrology

Feasibility Study of Microplasma High-brightness EUV Source at 13.5 nm (S13)
Takeshi Higashiguchi[1], Yoichi Hirose[1], Yuhei Suzuki[1], Takamitsu Otsuka[1], Jun-ichiro Sugisaka[1], Akira Endo[2], Padraig Dunne[3], and Gerry O'Sullivan[3]
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[3]*School of Physics, University College Dublin, Belfield, Dublin 4, Ireland*

Diagnostics and Modeling of Gas Puff Target Laser Plasma Radiation Source (S18)
Sarka Vondrova[1], Dalibor Panek[1], Petr Bruza[1], Miroslava Vrbova[1], Pavel Vrba[2], Przemyslaw Wachulak[3],Frantisek Krejci[1, 4], Jan Jakůbek[4]
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[4] Czech Technical University in Prague, Institute of Experimental and Applied Physics, 128 00 Prague 2, Czech Republic

In-situ Diagnostics for Plasma based Extreme Ultraviolet Sources (S22)

T. W. Versloot, F.T. Molkenboer, H.H.P.Th. Bekman, N.B. Koster, E. te Sligte, R. Verberk, R.C.M. Pohlmann, F.H. Elferink
TNO Delft, Stieltjesweg 1, 2628 CK, Delft, the Netherlands

Laser-initiated Discharge-produced Plasma Ablated from Liquid Metal Electrodes (S26)

Vasily S. Zakharov[1*], Larissa Juschkin[2], Sergey V. Zakharov[1*+], Gerry O'Sullivan[3], Emma Sokel[3], Isaac Tobin[4]
[1] EPPRA sas, Villebon sur Yvette, France
in collaboration with KIAM RAS, Moscow, Russia
[2] RWTH Experimental Physics, Aachen, Germany
[3] University College Dublin, Ireland
[4] Trinity College Dublin, Ireland
** also with NRC Kurchatov Institute, Moscow, Russia*
[+] also with JIHT RAS and SRC RF TRINITI, Moscow, Russia

EUV Emission from Laser-triggered Z-pinch Discharge (S30)

Isaac Tobin[1], Larissa Juschkin[2,3], Fergal O'Reilly[2],
Paul Sheridan[4], Emma Sokel[2], James G. Lunney[1]
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[4]Newlambda Technologies, UCD Science Centre North, Belfield, Dublin 4, Ireland.

Topic: Applications of EUV Sources

R&D Actinic Blank Inspection Microscope (S40)

Larissa Juschkin[1], Stefan Herbert[2], Aleksey Maryasov[2], Serhiy Danylyuk[2], Rainer Lebert[3]
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[3]Bruker Advanced Supercon GmbH, Waltherstrasse 49-51, 51069 Köln, German

Exploring the Resolution Limit of the Talbot lithography with EUV Light (S41)

Hyun-su Kim[1], Serhiy Danylyuk[2], Sascha Brose[2], Klaus Bergmann[3],
Detlev Grützmacher[4], Larissa Juschkin[1]
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[4]Peter Grünberg Institute 9 (PGI-9): Semiconductor Nanoelectronics, Research Center Jülich
and JARA - Fundamentals of Future Information Technology (FIT), 52425 Jülich, Germany

Topic: Modeling

Modeling of Absorption and Scattering of IR laser Radiation by LPP Targets (S53)

A. S. Grushin[1,2], I. P. Tsygvintsev[1,2], V. G. Novikov[1,2], V. V. Ivanov[1,3]
[1]RnD-ISAN, Troitsk, 142090 Russia
[2]Keldysh Institute of Applied Mathematics RAS, Moscow, 125047 Russia
[3]Institute for Spectroscopy RAS, Troitsk, 142090 Russia

Modeling of Plasma Dynamics and EUV Generation for Distributed Sn Targets Irradiated with Short Laser Pulses (S54)

V. Ivanov[1], A. Grushin[2], V. Novikov[2], V. Medvedev[3], V. Krivtsun[1], A. Yakunin4, and K. Koshelev[1]
[1]Institute for Spectroscopy RAS, Troitsk, Russia
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[3]Dutch Institute for Fundamental Energy Research, Nieuwegein, The Netherlands
[4]ASML, The Netherlands

Topic: BEUV

Alternative Future 6.x nm EUV Sources from Strong In-band Line Emission (S29)

Thomas Cummins[1], Takamitsu Otsuka[2], Tony Donnelly[1], Weihua Jiang[3], Akira Endo[4],
Padraig Dunne[1], Gerry O'Sullivan[1] and Takeshi Higashiguchi[2]
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[4] HiLASE Project, Institute of Physics AS, CR, Na Slovance 2, 182 21 Prague 8, Czech Republic

A Tunable Beyond Extreme Ultraviolet Source at 6.x nm based on a Laser-produced Plasma from a High-*Z* Target Mix (S32)

Colm O'Gorman[1], Takamitsu Otsuka[2], Weihua Jiang[3], Akira Endo[4], Bowen Li[1], Thomas Cummins[1], Padraig Dunne[1], Emma Sokell[1], Gerry O'Sullivan[1], and Takeshi Higashiguchi[2]
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[4] *HiLASE Project, Institute of Physics AS, CR, Na Slovance 2, 182 21 Prague 8, Czech Republic*

Identification of Atomic Resonances for Enhancement of High Harmonic Generation in Laser-produced Plasmas (S35)

R. Stefanuik[a], N. Krstulovic[a], M. Mahmoad[b], P. Dunne[a], G. O'Sullivan[a]
a:School of Physic, University college Dublin, Ireland
b: Institute Of Lasers for postgraduate studies, University of Baghdad, Iraq

EUV Spectra of Highly Charged Heavy Ions in the NIST EBIT (S60)

D. Kilbane[a], J. D. Gillaspy[b], Yu. Ralchenko[b], J. Reader[b], G. O'Sullivan[a]
[a] *School of Physics, University College Dublin, Belfield, Dublin 4, Ireland*
[b] *National Institute of Standards and Technology, Gaithersburg, MD 20899, USA*

Topic: XUV

Possibility of High-*Z* Plasma Water Window Sources (S14)

Takeshi Higashiguchi[1], Takamitsu Otsuka[1], Weihua Jiang[2], Akira Endo[3], Bowen Li[4], Deirdre Kilbane[4], Padraig Dunne[4], and Gerry O'Sullivan[4]
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A Capillary Discharge-preformed Argon Plasma Waveguide for a Coherent Soft X-ray Source (S15)

Shohei Sakai[1], Takeshi Higashiguchi[1], Nadezhda Bobrova[2], Pavel Sasorov[2], and Noboru Yugami[1]

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Measurement of Spectra in Water- window Wavelength Region (S23)
J. Novak[1], M. Nevrkla[1], A. Jancarek[1], M. Vrbova[2], P. Vrba[3]
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Characterization of Capillary Discharge Water-Window Radiation Source (S24)
Michal Nevrkla[1], Jan Novak[1], Alexandr Jancarek[1], Pavel Vrba[2], Miroslava Vrbova[3]
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Emission Properties of Non-equilibrium Zirconium Plasma in Soft X-ray Region (S33)
Vasily S. Zakharov*, Sergey V. Zakharov *+
EPPRA sas, Villebon sur Yvette, France
in collaboration with KIAM RAS, Moscow, Russia
** also with NRC Kurchatov Institute, Moscow, Russia*
+ also with JIHT RAS and SRC RF TRINITI, Moscow, Russia

A Commercial Laboratory Soft-X-ray Source for Water Window Microscopy (S37)
Stephen F. Horne, Matthew M. Besen, Donald. K Smith
Energetiq Technology, Inc., 7 Constitution Way, Woburn, MA, USA 01801

Spectral Characterization of XUV Sources based on Plasmas Induced by Laser and Capillary Discharge (S38)
P. Kolar[1], D. Panek[1], M. Vrbova[1], M. Nevrkla[2], P. Vrba[3], and A. Jancarek [2]
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XUV Spectroscopy of the Interaction of Laser-produced Plasma with Solid Surfaces (S42)

A S Kuznetsov[1], R Stuik[2], F Bijkerk[1,3], Eric Louis and A P Shevelko[4].
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[4] *P.N. Lebedev Physical Institute of the Russian Academy of Sciences, 117924 Moscow, Russia*

Wednesday, October 10, 2012

8:30 AM Announcements

Introduction and Announcements (Intro-2)
Vivek Bakshi, EUV Litho, Inc.

Poster Session Awards and Announcements
Padraig Dunne (UCD)

8:40 AM Session 9: Keynote-2

Session Chair: Padraig Dunne (UCD)

Microfocus Sources for EUV and X-ray Applications (S3)
Alan Michette
Department of Physics, King's College London, Strand, London WC2R 2LS, UK

9:35 AM Session 10: Business Presentations

Session Chair: Padraig Dunne (UCD)

Erasmus Mundus Joint Doctorate Programme EXTATIC (*EUV and X-Ray Training in Advanced Technologies for Interdisciplinary Cooperation*) - Program Review (S48)
Paul van Kampen
School of Physical Sciences, Dublin City University, Dublin, Ireland

10:05 AM Break (20 Minutes)

10:20 AM Session 11: BEUV

Session Co-Chairs: Udo Dinger (Carl Zeiss) and Takeshi Higashiguchi (Utsunomia University)

Plasma-based UTA Emission in BEUV & Water Window Spectral Regions (S11) (Invited Paper)
Takeshi Higashiguchi[1], Takamitsu Otsuka[1], Weihua Jiang[2], Akira Endo[3], Thomas Cummins[4], Colm O'Gorman[4], Bowen Li[4], Deirdre Kilbane[4], Padraig Dunne[4], and Gerry O'Sullivan[4]
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Dual Laser Plasma Photoabsorption Studies Of Gadolinium In The Extreme Ultraviolet Region (S34) (Invited Paper)
Paddy Hayden, C. Fallon, T. J. Kelly and J. T. Costello
School of Physical Sciences/National Centre for Plasma Science and Technology, Dublin City University, Glasnevin, Dublin 9, Ireland

Highlights from a Recent BEUV Source Workshop (September 26, 2012, Japan) (S12)
Takeshi Higashiguchi
Utsunomiya University

Concept Study on an Accelerator based Source for 6.x nm Lithography (S16)
Udo Dinger[1], Diana Tuerke[1], Atoosa Meseck[2], Michael Patra[1], Erik Sohmen[1], Andreas Jankowiak[2]
[1] Carl Zeiss SMT GmbH, Rudolf – Eber - Straße 2, 73447 Oberkochen
[2] Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Hahn-Meitner-Platz 1, 14109 Berlin

Session 12: XUV and Applications

Session Co-Chairs: Ladislav Pina (RIT-Europe) and Rainer Lebert (Bruker)

High-brightness Liquid-jet Laser-plasma Enabling 10-second-exposure Water-window Cryo Microscopy (S43) (Invited Paper)

M. Selin[1], D. H. Martz[1], O. von Hofsten[1], E. Fogelquist[1], A. Holmberg[1], U. Vogt[1], H. Legall[2], G. Blobel[2], C. Seim[3], H.Stiel[2], and H. M. Hertz[1]
[1]*Biomedical and X-Ray Physics, Dept. of Applied Physics, KTH Royal Inst. of Technology/Albanova, 10691 Stockholm, Sweden*
[2]*Max-Born-Institut, Max-Born-Straße 2A, 12489 Berlin, Germany*
[3]*Institute of Optics and Atomic Physics - Analytical X-ray physics, Technische Universität Berlin, 10623 Berlin, Germany*

Whole Cell Cryogenic Soft X-ray Tomography with a Laboratory Light Source (S21) (Invited Paper)

D.B. Carlson[1], J. Gelb[2], V. Palshin[2] and J.E. Evans[1,3,*]
[1]*Dept. of Molecular and Cellular Biology, University of California at Davis, Davis, CA, USA*
[2]*Xradia, Inc., Pleasanton, CA, USA*
[3]*Pacific Northwest National Lab, Environmental Molecular Sciences Lab, Richland, WA, USA*

Capillary Plasma Radiation Source in the Soft X-Ray Region (S17)

Pavel Vrba[1], Miroslava Vrbova[2], Sergey V. Zakharov[3], Vasiliy S. Zakharov[3,4] Alexandr Jancarek[5], Michal Nevrkla[5]
[1] *Institute of Plasma Physics, Academy of Sciences, 182 00 Prague 8, Czech Republic*
[2] *Czech Technical University, Faculty of Biomedical Engineering, 272 01 Kladno, Czech Republic*
[3]*EPPRA sas, Villebon / Yvette, France*
[4] *KIAM RAS, Moscow, Russia*
[5] *Czech Technical University, Faculty of Nuclear Sci. and Phys. Engineering, 115 19 Prague 1, Czech Republic*

XUV and EUV Applications with EUV Sources for Metrology (S46) (Invited Paper)

Rainer Lebert, Thomas Mißalla, Azadeh Farahzadi, Christoph Phiesel, Urs Wiesemann, and Wolfgang Diete
Bruker Advanced Supercon GmbH, Waltherstrasse 49-51, 51069 Köln-Dellbrück, Germany

12:40 PM Workshop Summary and Announcements

Workshop Summary and Announcements (Summary-Source Workshop)
Vivek Bakshi, EUV Litho, Inc.

1:00 PM Workshop Adjourned

1:00 Leave for Lunch and Tour (Wicklow Historic Gaol and area)

Thursday, October 11, 2012

Location: Newman House, Stephen's Green, Dublin

Technical Working Group (TWG) Meeting

8:30 AM	Breakfast
9:00 AM – 10:00 AM	TWG Meeting

ABSTRACTS

S1

High Repetition Rate Table-top Soft X-Ray Lasers

J. J. Rocca[1,2,3], B. Reagan [1,2], Y. Wang,[1,2] , D. Alessi, B. M. Luther[1,2], K. Wernsing[1,2], L. Yin [1,2] , M. A. Curtis [1,2], M. Berrill[1,2] , D. Martz [1,2] , V.N. Shlyaptsev[1,2] , S. Wang [1,2] , F. Furch [1,3], M. Woolston [1,2], D. Patel [1,2], C.S. Menoni [1,2]

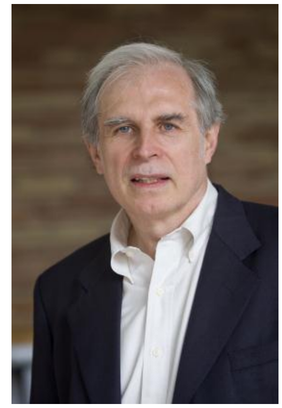
[1] *National Science Foundation ERC for Extreme Ultraviolet Science and Technology*
[2] *Electrical and Computer Engineering Department, Colorado State University, Fort Collins, CO 80523*
[3] *Physics Department, Colorado State University, Fort Collins, CO 80523*

We will discuss recent advances in the development of high repetition rate table-soft soft x-ray lasers resulting from work at Colorado State University that significantly increase the repetition rate and average power of table-top soft x-ray lasers. These advances include the first demonstration of a 100 Hz repetition rate table-top soft x-ray laser, and the efficient generation of gain-saturated sub-9-nm wavelength picosecond laser pulses of micro joule energy at 1 Hz repetition rate [1].

Gain-saturated lasing was obtained at λ=8.85 nm by collisional electron impact excitation of nickel-like lanthanum ions in a pre-created plasma column heated by a picosecond optical laser pulse. Furthermore, isoelectronic scaling along the lanthanide series resulted in lasing at wavelengths as short as 7.36 nm. We will also discuss progress in the development of high repetition rate diode-pumped table-top soft x-ray lasers. Efficient pumping of the soft x-ray driver laser with diode lasers opens the possibility to develop a new generation of more compact soft x-ray lasers capable to operate at significantly increased repetition rates and larger average powers for applications. We have previously reported the demonstration of a diode pumped soft x-ray laser operating at 10 Hz repetition rate in the λ = 18.9 nm line of Ni-like Mo ions using a diode-pumped Yb:YAG chirped-pulse-amplification pump laser system. Recently we have operated this compact laser at 100 Hz repetition rate for the first time to achieve an average power of 0.15 mW, the highest average power obtained to date from a table-top coherent source at sub-20 nm wavelengths. The increase in photon flux that results from operating compact soft x-ray lasers at high repetition rates will open up new applications.

1. D. Alessi, Y. Wang, D. Martz, B. Luther, L. Yin, D.H. Martz, M.R. Woolston, Y. Liu, M. Berrill, and J.J. Rocca, "Efficient excitation of gain-saturated sub-9 nm wavelength table-top soft X-ray lasers and lasing down to 7.36 nm", Physical Review X , **1**, 021023 (2011)

Presenting Author



Jorge J. Rocca is a University Distinguished Professor at Colorado State University, in the Department of Electrical and Computer Engineering and the Department of Physics. Professor Rocca's research concentrates mostly in the development and physics of compact soft x-ray lasers and their applications, and in the study of dense plasmas, subjects in which he has published more than 200 peer review journal papers. His group demonstrated the first gain-saturated table-top soft x-ray laser using a discharge plasma as gain medium, and later extended the wavelength of bright high repetition rate table-top lasers down to 8.8 nm using laser-created plasmas. Early in his career Rocca was an NSF Presidential Young Investigator. He is a Fellow of the American Physical Society, the Optical Society of America, and the Institute of Electrical and Electronics Engineers. He was the recipient of a Distinguished Lecturer Award from IEEE in 2008, the Schawlow Prize in Laser Science from the American Physical Society in 2011, and the Willis E .Lamb Award for Laser Science and Quantum Optics in 2012.

S2

Extendibility of LPP EUV Source Technology in Higher Power (kW) and Shorter Wavelength (6.x nm) Operation

Akira Endo

Waseda University, Tokyo, Japan
HiLASE Project, Prague, Czech Republic

The basic architecture of double pulse method is explained as the higher CE is available together with full target mass recovery due to full ionization of injected micro Tin droplets at high repetition rate. Much higher repetition rate is desirable for increase of output power, and the physical limit on this approach is explained by the plasma behavior in magnetic field. BEUV operation is explained as the extension of the double pulse method to Gd/Tb micro droplets, and expected CE is estimated from recent experiments as 1.5%/0.6% bandwidth.

Presenting Author

Prof. Dr. A. Endo worked in various fields in high power lasers and short wavelength research, and joined in EUVA to work as a research leader of EUV light source in 2002. High average power, pulsed laser was the first requirement. Pulsed CO_2 laser was initially tested to generate EUV emission with surprising positive results. Intensive research showed 20kW average power available by pulsed CO_2 laser architecture. Another issue was to avoid damage by fast particles from plasma. A suitably designed magnetic field could guide the plasma flow to a diverter installed outside the vacuum chamber. The demonstrated method is now under integration by Industry.
He stayed in 2009 in Jena, Germany as the 10^{th} Carl Zeiss Guest Professor to give a series of lectures on the newly developed EUV source. This lecture attracted many audiences in University and Companies. This lecture was summarized in a book chapter as *CO_2 laser produced Tin plasma light source as the solution for EUV lithography, Chapter 9, Lithography Edited by Michael Wang, InTech, February (2010).* This article had more than 1000 readers until the end of 2011.
He is now a guest professor in a research group of laser-Compton X-ray source in Waseda University, and a research leader of a high average power, pulsed solid state laser in HiLASE project in Prague, Czech Republic.

S3

Microfocus Sources for EUV and X-ray Applications

Alan Michette

Department of Physics, King's College London, Strand, London WC2R 2LS, UK

Applications utilizing short wavelength radiation are becoming increasingly demanding on the properties of the source and the associated optics. It is well known that facilities such as synchrotrons and free-electron lasers offer exceptional source qualities, but for routine analytical, technical or commercial applications it is widely recognized that more readily available systems must be developed.

This presentation will summarize the work of the COST Action MP0601 *Short Wavelength Laboratory Sources*, including source modeling and development as well as the coupling to suitable optical systems. Some exemplar applications will also be described. The talk will conclude with a look to the future as the new COST Action MP1203 *Advanced Spatial and Temporal X-ray Metrology* gets underway.

Presenting Author

Alan Michette is a Professor of Physics and the Head of the Physics Department at King’s College London. He has been carrying out research into X-ray sources and optics, and their applications, for over 30 years, in some senses carrying on from previous researchers at King’s such as Maxwell, Barkla, Franklyn, Wilkins and Hart. His current interests are related to studies of radiation-induced cancers using microfocus X-ray sources and novel X-ray optics.

S10

EUV Lithography: Today and Tomorrow?

Vadim Banine

ASML, The Netherlands

EUV lithography has come a long way over the last two decades starting from small field demonstration systems through full field alpha tool scanners installed in 2006 in CNSE, Albany, USA and IMEC, Leuven, Belgium to EUV followed by multiple pre-production tools installed at customer locations since 2010.

Starting with historical perspective, mid- and long-term challenges for the source will be reviewed.

EUV can be extended for several nodes by a combination of advanced illumination schemes, higher numerical aperture and potentially new wavelength. Worldwide research activities supporting this EUV extension will be shared and discussed.

Presenting Author

Dr. Vadim Banine is currently Director of Research at ASML. He has worked for ASML since 1996 and has held positions of Senior Research Manager, Head of ASML laboratory and external project co-ordinator for ASML research department. He received his PhD in 1994 from Eindhoven University of Technology, The Netherlands (TUE). The subject of his PhD work was the diagnostics of combustion plasma. From 1995-96 he did his postdoctoral work at TUE in the Laboratory of Heat and Mass Transfer. He has over 40 publications and over 100 patens. He is also the winner of ASML patent award.

S11

Plasma-based UTA Emission in BEUV & Water Window Spectral Regions

Takeshi Higashiguchi[1], Takamitsu Otsuka[1], Weihua Jiang[2], Akira Endo[3], Thomas Cummins[4],
Colm O'Gorman[4], Bowen Li[4], Deirdre Kilbane[4], Padraig Dunne[4], and Gerry O'Sullivan[4]

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[2]Department of Electrical Engineering, Nagaoka University of Technology, Kami-tomiokamachi 1603-1, Nagaoka, Niigata 940-2188 Japan
[3]HiLASE Project, Institute of Physics AS, CR, Na Slovance 2, 18221 Prague 8, Czech Republic
[4]School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

We demonstrate the EUV and soft x-ray sources in the 2 to 7 nm spectral region related to the beyond EUV (BEUV) question at 6.x nm [1-7] and the water window source [8] based on laser-produced high-*Z* plasmas. Resonance emission from multiply charged ions merges to produce intense unresolved transition arrays (UTAs), extending below the carbon K edge (4.37 nm). An outline of a microscope design for single-shot live cell imaging is proposed based on high-*Z* plasma UTA source, coupled to multilayer mirror optics. We will discuss the value of x in 6.x-nm BEUV emission to optimize coupling with the recent multilayer mirror developed by FOM. In addition, and we will propose new scheme for a microscope in water window spectral region.

[1] T. Otsuka *et al*., Appl. Phys. Lett. **97**, 111503 (2010); G. Tallents *et al*., Nat. Photonics **4**, 809 (2010).
[2] T. Otsuka *et al*., Appl. Phys. Lett. **97**, 231503 (2010).
[3] T. Higashiguchi *et al*., Appl. Phys. Lett. **99**, 191502 (2011).
[4] B. Li *et al*., Appl. Phys. Lett. **99**, 231502 (2011).
[5] T. Cummins *et al*., Appl. Phys. Lett. **100**, 061118 (2012).
[6] C. O'Gorman *et al*., Appl. Phys. Lett. **100**, 141108 (2012).
[7] B. Li *et al*., Appl. Phys. Lett. **101**, 013112 (2012).
[8] T. Higashiguchi *et al*., Appl. Phys. Lett. **100**, 014103 (2012).

Presenting Author

Takeshi Higashiguchi is an associate professor. He received his Ph.D. in engineering from Utsunomiya University. His research activities have focused on short-wavelength light sources, laser-plasma interaction, and hybrid laser system.

S13

Feasibility Study of Microplasma High-brightness EUV Source at 13.5 nm

Takeshi Higashiguchi[1], Yoichi Hirose[1], Yuhei Suzuki[1], Takamitsu Otsuka[1], Jun-ichiro Sugisaka[1],
Akira Endo[2], Padraig Dunne[3], and Gerry O'Sullivan[3]

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[2]HiLASE Project, Institute of Physics AS, CR, Na Slovance 2, 18221 Prague 8, Czech Republic
[3]School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

We investigated the feasibility of using a microplasma high-brightness EUV source at 13.5 nm as a metrology source. Compared with the HVM case specific requirements for metrology sources have not yet been specified. The light source needs to be stable, small with an etendue in the order of 0.03 mm^2sr, and high-brightness with a few watts of power. The microplasma for a metrology source should be produced to be the order of 10-20 um with a millijoule per pulse. We show a proof-of-principle experiment by use of a microtarget with a diameter of 10 microns with a thickness of 100 nm, and the results are supported by numerical simulation.

Presenting Author

Takeshi Higashiguchi is an associate professor. He received his Ph.D. in engineering from Utsunomiya University. His research activities have focused on short-wavelength light sources, laser-plasma interaction, and hybrid laser system.

S14

Possibility of High-*Z* Plasma Water Window Sources

Takeshi Higashiguchi[1], Takamitsu Otsuka[1], Weihua Jiang[2], Akira Endo[3], Bowen Li[4], Deirdre Kilbane[4], Padraig Dunne[4], and Gerry O'Sullivan[4]

[1]Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), and Optical Technology Innovation Center (OpTIC), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan
[2]Department of Electrical Engineering, Nagaoka University of Technology, Kami-tomiokamachi 1603-1, Nagaoka, Niigata 940-2188 Japan
[3]HiLASE Project, Institute of Physics AS, CR, Na Slovance 2, 18221 Prague 8, Czech Republic
[4]School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

UTA (unresolved transition array) emission from highly ionized high-*Z* materials, such as Sn, Xe, Gd and Tb can be optimized for high conversion efficiencies greater than 1% in the extreme ultraviolet (EUV) spectral region. The UTA is scalable to shorter wavelengths, and Gd was shown to have a similar conversion efficiency to Sn (13.5 nm) at a higher plasma temperature, with a narrow spectrum centered at 6.7 nm, where a 70% reflectivity mirror is anticipated. We demonstrate a table-top broadband emission water window source based on laser-produced plasmas. Resonance emission from multiply charged ions merges to produce intense UTAs in the 2 to 4 nm region, extending below the carbon K edge (4.37 nm). An outline of a microscope design for single-shot live cell imaging is proposed based on a bismuth plasma UTA source, coupled to multilayer mirror optics.

Presenting Author

Takeshi Higashiguchi is an associate professor. He received his Ph.D. in engineering from Utsunomiya University. His research activities have focused on short-wavelength light sources, laser-plasma interaction, and hybrid laser system.

S15

A Capillary Discharge-preformed Argon Plasma Waveguide for a Coherent Soft X-ray Source

Shohei Sakai[1], Takeshi Higashiguchi[1], Nadezhda Bobrova[2], Pavel Sasorov[2], and Noboru Yugami[1]

[1]Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), and Optical Technology Innovation Center (OpTIC), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan
[2]Institude for Theoretical and Experimental Physics, B. Cheremushkinskaya str. 25, 117218 Moscow, Russia

We have reported the argon plasma waveguide produced in an alumina capillary discharge and used to guide ultrashort laser pulses at intensities of the order of 10^{16} W/cm^2 for coherent soft x-ray radiation by use of soft x-ray laser and/or high order harmonics. The electron density in the plasma waveguide was measured to be 1 x 10^{18} cm^{-3}, in agreement with one-dimensional MHD simulations. A maximum ion charge state of Ar^{3+} was measured in the capillary discharge and also obtained in our MHD simulations. The spectrum of the propagated laser pulse in the Ar plasma waveguide was not modified and was well reproduced by PIC simulations under an initial ion charge state of Ar^{3+} in the preformed plasma waveguide. We discuss the possibility of the compact, coherent soft x-ray source in this presentation.

Presenting Author

Shohei Sakai is a Ph.D. student in Department of Innovation Systems Engineering at Utsunomiya University. His research activities have focused on terahertz radiation source and laser-plasma interaction. He is working at Tanaka Scientific Ltd. as a senior engineer and his main charge is R&D of EDXRF and WDXRF of the sulfur analyzer.

S16

Concept Study on an Accelerator based Source for 6.x nm Lithography

Udo Dinger[1], Diana Tuerke[1], Atoosa Meseck[2], Michael Patra[1], Erik Sohmen[1], Andreas Jankowiak[2]

[1] Carl Zeiss SMT GmbH, Rudolf – Eber - Straße 2, 73447 Oberkochen
[2] Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Hahn-Meitner-Platz 1, 14109 Berlin

“Beyond EUV (BEUV) lithography” at 6.x nm calls for a source providing very high power in the 1 kW regime with a very small bandwidth at lowest possible etendue. Present baseline are laser plasma sources based on either Gadolinium or Terbium targets. Recently accelerator based sources have been brought into discussion as lithography sources in several presentations. However so far not all the special requirements imposed by driving a lithography tool have been taken into account properly. In this work a scenario for a source based on a SASE-FEL is presented. The components and requirements are defined to especially fulfill the needs of lithography and checked for feasibility. In our presentation we will focus on key features like footprint, output power, invest and operational costs in a lithography system and give a rough idea of their numbers.

Presenting Author

S17

Capillary Plasma Radiation Source in the Soft X-Ray Region

Pavel Vrba[1], Miroslava Vrbova[2], Sergey V. Zakharov[3], Vasiliy S. Zakharov[3,4]
Alexandr Jancarek[5], Michal Nevrkla[5]

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[2] Czech Technical University, Faculty of Biomedical Engineering, 272 01 Kladno, Czech Republic
[3]EPPRA sas, Villebon / Yvette, France
[4] KIAM RAS, Moscow, Russia
[5] Czech Technical University, Faculty of Nuclear Sci. and Phys. Engineering, 115 19 Prague 1, Czech Republic

Plasma dynamics and emission characteristics of pinching capillary discharge simulated by Z*code are presented and compared with experimental results. The investigated setup consisted of capillary with radius R_0 = 0.16 cm, length L = 10 cm filled by nitrogen, connected to capacitor C = 21 nF, charged to U0 = 70 kV. Both calculated and measured current profiles were near to dumped sinus with the peak value ~23 kA and the half period ~150 ns. The output power of emission in the “water window” at the wavelength λ = 2.88 nm depends on the initial nitrogen pressure. The time dependences of the emitted power in the line have pulse profiles with two remarkable peaks. The highest peak value at the pinch time was ~1.8 MW at pressure ~100 Pa. The plasma electron temperature 40 eV < Te < 80 eV was noticed in the column with the radius ~ 600 μm. The estimated pulse emitted energy 5.5 mJ.sr-1 (~10^{14} photons.sr-1) corresponds properly to observed experimental value. Ray tracing inspection along the capillary axis proved reasonable role of self-absorption at the investigated wavelength. The time dependences of plasma parameters in the capillary centre were used as input data for FLYCH code. The spectra evaluated by the code agree to the measured ones.

Presenting Author

Professor Miroslava Vrbova, graduated in Physical Electronics from the Czech Technical University in Prague (CTU), received Ph.D. degree in Quantum Electronics and Optics from the same university. Now, she is working as a professor of Applied Physics at the Department of Natural Sciences, CTU- Faculty of Biomedical Engineering.

S18

Diagnostics and Modeling of Gas Puff Target Laser Plasma Radiation Source

Sarka Vondrova[1], Dalibor Panek[1], Petr Bruza[1], Miroslava Vrbova[1], Pavel Vrba[2], Przemyslaw Wachulak[3],Frantisek Krejci[1, 4], Jan Jakůbek[4]

[1]*Czech Technical University in Prague, Faculty of Biomedical Engineering, 272 01 Kladno, Czech Republic*
[2] *Institute of Plasma Physics, Academy of Sciences, 182 00 Prague 8, Czech Republic*
[3]*Military University of Technology, Institute of Optoelectronics, 00-908 Warszawa 49, Poland*
[4] *Czech Technical University in Prague, Institute of Experimental and Applied Physics, 128 00 Prague 2, Czech Republic*

Here we present a study of XUV emission characteristics of nitrogen plasma induced by infrared laser pulse (800 mJ / 7 ns) focused into a gas puff target. Spatial distribution of nitrogen density was determined by EUV radiography at the wavelength 13.5 nm. We used Gaussian function to approximate the cross-section of the gas puff target in the direction perpendicular to the axis of the nozzle. The value of target mass density was estimated to be $3.7\cdot10^{-4}$ g/cm^3 at the distance Δz = 0.5mm from the nozzle and $4.9\cdot10^{-4}$ g/cm^3 at Δz = 0.25 mm from the nozzle. The resulting density profile at the focal region and measured time dependences of laser power were introduced as input data to 2D RMHD (Radiation-Magneto-Hydro-Dynamic) code Z* (EPPRA s.a.s, France). Spatial developments of nitrogen plasma quantities were modeled. The evaluated electron temperature at the center of gas puff target exceeded the value Te ~ 34 eV. The related peak value of emitted energy density, in the wavelength region 2.8766 – 2.8867 nm approached the value Q_{euv} ~ 0.3 J/cm^3. The evaluated spatial distributions of emitted energy were compared with the experimental data obtained with a compact laser-based XUV source (Laser-Laboratory Göttingen e.V., Germany).

Presenting Author

Sarka Vondrova works in the Institute of Optoelectronics (IOE), Military University of Technology, Warsaw, Poland, in the area of EUV Sources. In 2011, she received her PhD in the department of Biomedical Engineering Czech Technical University (CTU), Prague, Czech Republic with specialization in the area of Soft X-Ray and XUV Radiation. She received her Masters in the department of Electrical Engineering, CTU in Prague, Czech Republic with specialization in Biomedical Engineering. Her Bachelor degree in 2008 is from Nuclear Sciences and Physical Engineering CTU in Prague with a specialization in Laser technology and optoelectronic.

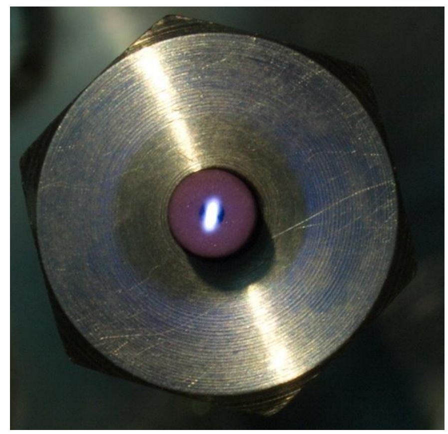
S19

EUV Emission from Xe gas Target Laser Plasma Pre-ionized with the UV Laser Light

Serguei Kalmykov, Alexey Mozharov, Mikhail Petrenko, Maxim Sasin

Ioffe Physical-Technical Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia

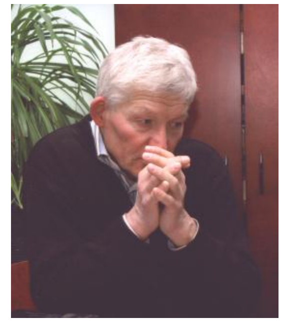
To avoid undesirable self-absorption of the EUV-radiation in outer non-ionized gas, density of the Xe gas-puff target should be of 10^{18} cm^{-3} in order of magnitude. Estimations and experiments performed earlier (Dublin-2011 EUV Workshop, S25) had demonstrated very slowed primary ionization in the laser plasma generated in such low density target by means of a standard ND:YAG laser – process of ionization up to Xe^{+1} took about a half of the laser pulse.



Stretched along the beam, the spark generated by the UV excimer laser (λ = 248 nm) at reduced pulse energy (≈ 60 mJ). A black hole just behind the spark (at the distance of 1 mm) is the 1.1 mm-diameter output nozzle orifice.

In the present work, UV excimer laser radiation (λ = 248 nm) is applied as a pre-ionization agent to accelerate the plasma ionization dynamics and thereby to enhance the EUV output. By now, work on targeting of both the laser beam foci onto the gas jet has been completed (see photo), comparative experiments on measuring EUV emission from the laser plasma with and without the pre-ionization are expected to get start in August.

Presenting Author



Serguei Kalmykov was born March 6, 1939 in Leningrad, Soviet Union, in 1962 graduated from the Polytechnical Institute (now St. Petersburg State Polythechnical University) and had been put in the research staff of the Ioffe Institute (St. Petersburg) where I continue working until now. Candidate of math sciences (physics/mathematics) degree from 1980 (this Russian scientific degree is approximately equivalent to PhD in Anglo-Saxon countries). Between 1962 and 2002 I was involved into the high temperature plasma and fusion area (general tokamak physics, magnetic confinement, transport processes) but then, in 2007, changed it for the laser plasma EUV source physics. Author/coauthor of approximately 60 scientific publications.

S20

Direct Diagnostics Concept for High Power CO_2 Laser at the LPP Focus Spot

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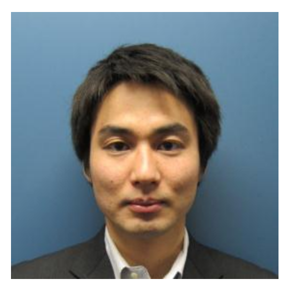
In the Laser Produced Plasma (LPP) EUV source, stability of CO_2 laser, which produces plasma, is the most important issue. The required CO_2 laser exceeds more than 100 kHz repetition 200 mJ pulse with 100 μ spot and 1ns pulse duration at the plasma point.

Direct diagnostics of such a high power pulse cannot be achieved by the recent technologies. Position, energy, and timing stabilities are necessary for stable EUV source, moreover, the ideal laser spot profile is also needed for higher conversion efficiency (CE). This presentation proposes the unique diagnostics for such high power laser pulses at the focus point.

This technique based on laser-Compton scattering with a very small spot electron beam.
Focused electron beam, of about 10micron size, is scanned over the laser spot as the SEM, the laser-Compton scattering photon has the information of the high power laser pulses.
If we scanned the electron beam from various direction, the laser focus profile can be obtained like a CT image.

We believe that this technique can provide the valuable information for stabilizing and optimizing the EUV source. The concept of this diagnostics, simulation studies of focused scanning electron beam, and future plans will be presented at the conference.

Presenting Author



Kazuyuki Sakaue is Assistant Professor of Applied physics department at Waseda University. He received a Ph. D degree in Accelerator Science from Waseda University. He has been active in the area of electron accelerators and laser-beam interactions for over 8 years. His current research involves study of high quality electron beam generation and the laser enhancement super-cavity system for upgrading the laser-beam interactions.

S21

Whole Cell Cryogenic Soft X-ray Tomography with a Laboratory Light Source

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Identifying the precise location of individual proteins or organelles within the cellular context has been a long held ambition of both structural and molecular biologists. Correlative light and electron microscopy attempts to address this goal by combining fluorescence data of specifically labeled proteins with ultrastructural details derived from transmission electron microscopy [1]. Unfortunately, to allow the transmission of electrons for high-resolution imaging, cellular material must be sectioned into thin slices thereby removing the direct link to whole cell fluorescence data. Recent advances in synchrotron based x-ray microscopy have empowered a third approach that bridges the spatial scales between fluorescence and electron microscopy [2].

While traditionally limited to synchrotron facilities alone, new advancements in compact light sources are now making soft x-ray microscopy available for routine laboratory characterization [3]. We will present the first multimodal correlative results from a novel soft x-ray microscope that incorporates a compact light source based on the Energetiq EQ-10 platform operating at 430 eV photon energy. The results highlight the ability of this approach for enabling a better understanding of the structure/function relationship of frozen hydrated whole cells up to 5 micrometers thick at spatial resolutions up to 50 nm.

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Presenting Author

James Evans is a Staff Scientist with Pacific Northwest National Laboratory. Dr. Evans obtained his PhD is Biochemistry from the University of California Davis with a focus on cryogenic aberration corrected electron microscopy. His current areas of research involve developing methods for improved multiscale imaging of biological structure and dynamics using electrons and x-rays including laboratory based cryogenic soft x-ray tomography, multimodal correlative microscopy and *in situ* aberration corrected dynamic transmission electron microscopy.

S22

In-situ Diagnostics for Plasma based Extreme Ultraviolet Sources

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Most sources for extreme ultraviolet (EUV) radiation are based on line emission from high temperature, high density plasmas. The obtained conversion efficiency from input power to the observed in-band EUV power will depend, among others, on the achieved plasma conditions. In order to further increase the EUV output, it is therefore vital to determine these plasma operating conditions. Currently, only limited direct diagnostic information from the plasma is available due to the harsh operating environment, short pulse duration and limited accessibility. Furthermore, in most cases dedicated diagnostics are relatively complex, spatially localized and costly.

At TNO we have developed several diagnostics that can be operated reliably within a source environment, e.g. infrared cameras and RGA’s. Recently we have also integrated several diagnostics into a single small size device that can be used for in-situ measurements. This prototype consists of a Langmuir probe, heat flux sensor, Faraday cup, photodiodes (UV/VIS) and a PT100. The sensor head can be positioned by a semi-rigid bellow and is mounted to either a vacuum compatible stand-alone data logger or flange feed-through.
Future developments are aimed towards long-duration testing this proof-of-principle device in an EUV environment and expanding the set of diagnostics.

Presenting Author

Thijs Versloot graduated from Twente University (Enschede, Netherlands) with a degree in Applied Physics in 2007. He received a PhD in Fusion Science and Technology in 2011 from the Eindhoven University of Technology on experimental diagnostic work carried out at the JET tokamak in the United Kingdom. His research is focused on experimental plasma physics, plasma diagnostics, plasma surface interactions and development of various types of plasma sources.

S23

Measurement of Spectra in Water- window Wavelength Region

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We demonstrate spectra measurement of nitrogen, argon and carbon dioxide as a possible source of XUV radiation in "water window" (2.2 - 4.4 nm) region. Capillary discharge system with 10 cm long, 3.2 mm inner diameter alumina capillary and peak current amplitude pulse of 21 kA was used. Our spectroscopic system has a resolution 0.03 nm and is composed from a silicon nitride free-standing transmission diffraction grating with 100 nm period and Reflex BICCD camera with frame size 512x512 pixels.

To find the best conditions for maximum output energy per steradian in one pulse measurement for eight different pressures were made for each gas. We recognized strong emission at these wavelengths 2.88 nm in nitrogen N VI, $1s^2$ - 1s2p, in argon 3.82 nm Ar X, $2s^22p^5$- $2s^22p^43d$ and 3.83 nm Ar XI, $2s^22p^4$ - $2s^22p^33s$, carbon dioxide 3.34 nm C V, $1s^2$ - $1s^4p$, 3.37 nm C VI, 1s - 2p and 4.03 nm C V, $1s^2$ - 1s2p. As a possible "water window" source could be used nitrogen at 2.88 nm, argon at 3.82 and 3.83 nm and carbon dioxide at 3.34 nm, 3.37 nm and 4.03 nm.

Presenting Author

S24

Characterization of Capillary Discharge Water-Window Radiation Source

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Intense XUV radiation in the “water-window” wavelength region, i.e. 2.3 - 4.4 nm, was generated by a Z-pinching capillary discharge in Nitrogen and Argon. The current driver is capable to deliver 23 kA in a pulse with rise-time of 50 ns into a 100 mm long, 3.2 mm diameter capillary. The output XUV radiation was characterized by following diagnostic methods: The time evolution of radiation emission from the capillary discharge Z-pinching Nitrogen and Argon plasma was measured by a XUV PIN diode in order to get radiation intensity and energy per pulse. Beam profile and divergence were measured via time-integrated image captured by a soft X-RAY BI-CCD camera. The radiation source size was found via a pinhole image. Spectral characteristics were obtained using a SiNx transmission grating. A 0.5 μm Titanium filter was used to select the wavelength region from 2.73 nm to approx. 6 nm. Optimization of initial gas pressure and discharge current amplitude was performed in order to find the maximal radiation intensity, energy per pulse, and maximal driver efficiency. Achieved output radiation intensities and energy in water-window wavelength region are: ~ 0.1 MW/srad (10 ns FWHM), ~ 3 mJ/srad/pulse (60 ns FWHM) in Nitrogen, and ~ 0.5 MW/srad (15 ns FWHM), ~ 20 mJ/srad/pulse (70 ns FWHM) in Argon. Driver repetition rate is 5 pps.

Presenting Author

Michal Nevrkla, is a PhD. student of Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague.

S25

Properties of High-intensity EUV & Soft-X Radiation Plasma Sources

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The high intensity radiation in plasma light sources is produced by multicharged ion non-equilibrium plasma. The innovative hybrid 2-3D computational code based on the Z^+ code and its commercially available version Z^+BME at EPPRA are further improved under international collaborative project FIRE FP7 IAPP to model radiating plasmas in experimental and industrial facilities using a hybrid approach including fast particles and plasma dynamics in an electromagnetic field, advanced atomic physics models and the spectral radiation transport. The code is used to model laser-produced plasma and discharge-produced plasma to understand current physical processes and to optimize the sources by brightness and delivered power of EUV & soft-X radiation for lithographic and metrology applications. The radiation plasma dynamics, the spectral effects of self-absorption in laser-produced plasma and discharge-produced plasma are considered. The radiance and conversion efficiency of laser energy to EUV radiation in tin LPP is discussed. The generation of fast electrons triggering a discharge and an enhancement of the radiance of a fast micro-plasma pulsed discharge created in a capillary wall confined structure is optimized. Without using an external physical optics, the EUV power can be focused by quasi-periodical self-consistent wave plasma structure. The power and brightness to required values can be increased through spatial and/or temporal multiplexing of low-etendue individual units. Static and dynamic combinations of 4 sources are considered. Fundamental understanding of Gd plasma emission with effects of radiation self-absorption has been done to move to 6.x nm waveband.

This work was performed in collaboration with in collaboration with KIAM RAS, Moscow, Russia.

Presenting Author

Dr. Sergey V. Zakharov graduated from the Moscow Institute of Physics and Technology**.** He received the doctor degree in physical-mathematical sciences from Kurchatov Institute of Atomic Energy, Moscow, Russia. In 1981-2005 he joined Troitsk Institute of Innovation and Fusion Research (TRINITI), Russia, in 1981, as a Head of the theoretical laboratory. In 1995-1998 he was a Professor of Moscow State Technology University, Russia. In 1993-1999 he was Director of Center of High Technologies ZENITH, Dolgoprudniy, Russia. Since 2005 he joined the Russian National Research Centre Kurchatov Institute as a Leading Scientist. His works concern plasma turbulence theory, nonlinear waves, charged particle beams, radiation-magnetohydrodynamics and non-equilibrium plasma theory in HEDP and ICF. For works on interaction of high power electron beams with dense gas he was rewarded the State Prize for young scientists and engineers in 1987. For researches on high energy density physics and radiating multicharged ion plasma he was rewarded the Great Government Reward in 1997. In 1997-1998 he joint Ecole Polytechnique, France as an Invited Senior Researcher. Since 1999 he joined EPPRA SAS, France, as a Principal Scientist and a Product manager. In 2009-2012 he also held the position as a Principle Scientist at NanoUV SAS, France, responsible on theory and modelling. Since 2010 he also joined with Joint Institute of High Temperatures of RAS, Moscow, Russia. He works on the theory of non-equilibrium heavy-ion plasmas and modelling of discharge and laser produced plasma radiation sources, in particular also for EUV lithography. Under his leadership the radiation-magnetohydrodynamic codes ZETA and Z* were created and are being developed. He has more than 250 scientific publications.

S26

Laser-initiated Discharge-produced Plasma Ablated from Liquid Metal Electrodes

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Laser-initiated discharge produced plasma system has been studied as a viable approach for the EUV lithography light source at 13.5 nm wavelength. The source is based on a discharge in tin or galinstan vapor produced by laser pulse between rotating disk electrodes. This paper focuses on the results of the computer modelling of that laser-induced discharge with the electrical circuit characteristics and laser beam parameters similar to the used in the experiment. Z*-code comprising recent advances in atomic physics and radiation-magnetohydrodynamics is used under international collaborative project FIRE in the framework of FP7 IAPP to model laser- and discharge-produced plasma dynamics and emission. Complex consideration of radiation from unresolved transition arrays includes the model of non-equilibrium ionization in plasma of multicharged ions based on detailed kinetic equations resolution with major electon-ion interaction processes taken into account. The radiation-plasma dynamics and the spectral effects of self-absorption in laser produced plasma and discharge produced plasma are considered. The simulation results are compared with experimental data. The detailed physics of the effects taking place in the laser-initiated discharge is discussed.

Presenting Author

S27

2D PIC Modeling of the EUV Induced Hydrogen Plasma and Comparison to the Observed Carbon Etching Rate

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The interaction between an EUV driven hydrogen plasma and a carbon covered surface was investigated using 2D PIC modeling and results were compared with experimental observations. The plasma is formed due to ionization of a low pressure hydrogen gas by the EUV photons and the photoelectrons from the surface. This results in ion fluxes to the surface, leading to the surface etching. We model the evolution of the plasma during and after the EUV pulse and obtain the energy resolved ion fluxes from the plasma to the surface. The carbon etching rates observed at various experimental conditions and estimated from computed ion fluxes for the same conditions agree under assumption that the etching yield is close to one carbon atom per incoming hydrogen ion.

Presenting Author

D.I. Astakhov is a PhD student in the nanolayer Surface & Interface physics (nSI) department in Dutch Institute for Fundamental Energy Research (DIFFER). His research interest is in modeling of cold plasmas. Received M.S. from Moscow Institute for Physics and Technology in 2009.

S28

High Brightness, High-average Power Picosecond Thin Disc Laser Program to Specific Requirements from Short Wavelength Light Sources

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Thin disc laser is the best solid state laser architecture to realize high brightness, high average power, and fast repetition rate picosecond pulses with precise spatial stability. HiLASE project is started from September 2011 and one program is aiming at achieving 500 W high beam quality pulses by this technology in the picosecond pulse duration at 100 kHz. Major applications are in the short wavelength light sources, like pre-pulse for dispersion of droplet target, micro plasma for metrology sources, HHG and RF photocathode illumination. Generally, thermally induced OPD (optical phase distortion) of thin disk limits the ultrashort pulse output up to few hundreds of watts, and degrades the pointing stability. We designed in-situ transient OPD measurement technique based on a precise wavefront sensor to compensate the OPDs and to achieve 500 W output with excellent spatial characteristics. The talk gives the overview of the program and shows the recent experimental progress.

Presenting Author

Taisuke Miura is a senior researcher of the HiLASE Project. He received his Ph.D. in engineering from Keio University. His present research activities are focused on high power ultrashort pulse generation based on Yb-doped thin disk laser technology.

S29

Alternative Future 6.x nm EUV Sources from Strong In-band Line Emission

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Research is proceeding into developing a light source for advancing beyond extreme ultraviolet (BEUV) as a feasible future lithography source. In this work we investigate possible alternative line emitters at 6.x nm due to the current uncertainty on the precise wavelength of multilayer mirrors. Photoemission spectroscopy of laser produced phosphorus (P) plasma was observed. By irradiating P targets, we demonstrate a viable alternative BEUV source at 6.x nm from strong line emission observed around 6.6 nm. Given that specific wavelengths of multilayer collector optics are not yet set, this could prove useful as a future source. COWAN code calculations were used to fit experimental spectra and show BEUV emission of P resulting mainly from the $2p^5 - 2p^4 3d$ transition array of the P VII ion. Calculations of charge state distributions of P plasma show that emission can be optimized at an electron temperature of around 40-50 eV, meaning optimal emission can be achieved at lower plasma temperatures than required for Gd or Tb laser produced plasmas. Comparing spectra of P with both Gd and Tb shows the peak emission is better suited to the reflectivity curves of currently available multilayer optics. Calculations of emission from Ne plasma also show its potential as a short wavelength source.

Presenting Author

Thomas Cummins is a 3rd year PhD student. He graduated with a B.Sc. in Applied Physics from Dublin City University in 2009 and joined the Spectroscopy group of University College Dublin in September 2009 as a PhD student. His research interests include laser produced plasma for development of Extreme Ultraviolet light sources, laser Sn plasma interaction and shorter wavelength BEUV sources. His project supervisor is Prof. Padraig Dunne.

S30

EUV Emission from Laser-triggered Z-pinch Discharge

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Current state-of-the-art prototype extreme ultraviolet (EUV) sources for lithography utilize tin plasma as the emitting material. We have compared the EUV emission characteristics at 13.5 nm for tin and galinstan in a laser-triggered Z-pinch discharge. Galinstan is a metal alloy (78.35% Ga, 14.93% In, 6.72% Sn) which is liquid at room temperature. The discharge source consists of two disc electrodes which rotate in shallow baths of liquid metal, and are thus coated with metal. A nanosecond laser pulse is used to form a laser produced plasma on one electrode. This plasma expands rapidly into the electrode gap and triggers a weakly damped discharge with a period of 0.6 µs and a peak current of 17 kA. The laser energy is adjusted to ensure that Z-pinching occurs at the first maximum of the discharge current.

The EUV emission was measured using an absolutely calibrated time integrating EUV spectrograph and in-band EUV filtered photodiode. The source was measured using EUV imaging and the plasma outflow was recorded using a Faraday cup ion detector. The energy conversion efficiency (CE) into 2π sr in a 2% band at 13.5 nm is found to be 0.22% for tin and 0.089% for galinstan for a 4 J discharge. Relative to tin the EUV emission for galinstan is higher than expected according to the percentage of tin, which may be due to the influence of optical opacity in the tin discharge.

Presenting Author

S31

Recent Progress on High Brightness Source Collector Module for EUV Mask Metrology

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NewLambda Technologies (www.NewLambda.com) are developing a high brightness source collector module for EUV mask metrology applications. The collector optic is a liquid metal coated ellipsoid section. The optic rotates slowly to maintain a uniform and stable thickness of liquid metal over the interior surface. The source is a laser produced plasma which uses the same liquid metal as the collector. This allows close proximity of the collector to the source without need for debris mitigation before the collector. Thus the module is being designed to deliver a clean, debris-free, high brightness source of 13.5 nm photons to match industry demands. We report on recent results from our prototype system.

Presenting Author

Paul Sheridan is a founding member of NewLambda Technologies. He received his Ph.D. in 2008 from UCD Dublin for work on double photo-electron spectroscopy. Since then he has worked on the development of EUV sources and collector optics. Previously he received his MSc in the development of novel targets for laser produced plasma EUV sources. He has over 10 years design experience of vacuum systems and vacuum automation.

S32

A Tunable Beyond Extreme Ultraviolet Source at 6.x nm based on a Laser-produced Plasma from a High-*Z* Target Mix

Colm O'Gorman[1], Takamitsu Otsuka[2], Weihua Jiang[3], Akira Endo[4], Bowen Li[1], Thomas Cummins[1], Padraig Dunne[1], Emma Sokell[1], Gerry O'Sullivan[1], and Takeshi Higashiguchi[2]

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An EUV source with tunable wavelength properties is demonstrated by mixing of the adjacent high-*Z* elements, Gd and Tb, in a complex target. The targets are irradiated by Nd:YAG lasers of pulse width 10 ns and 150 ps and their spectral emission in the 6.x nm region is observed. Emission from the complex target is compared to emission from pure Gd and Tb plasmas. It is shown that the spectral profile from the complex target is not simply an addition of emission from the two individual elements and that the change in profile is due to opacity effects. The emission is compared to theoretical spectra based on Cowan code calculations [1] coupled with a collisional radiative model [2]. It is envisaged that this tunable wavelength source could be matched to the reflectivity peak of a multilayer mirror for the development of an EUV source for lithography.

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Presenting Author

Colm O' Gorman is a PhD student with the Atomic, Molecular and Plasma Physics group in UCD. He received his B.Sc in Physics from University College Dublin in 2009. His research activities have focused on EUV emission spectroscopy and ion spectroscopy of laser produced plasmas.

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S33

Emission Properties of Non-equilibrium Zirconium Plasma in Soft X-ray Region

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Zirconium-based plasmas are considered as a source of soft X-ray emission in water window waveband alongside with nitrogen- and bismuth-based radiation plasma sources. Such discharge and laser produced plasmas used in soft X-ray (and EUV) sources are in non-equilibrium state as a rule. This leads to a mismatch between the actual conditions of the plasma and its theoretical/computational estimations because of different effects like non-thermal electron distribution, self-absorption etc. leading to changes in ionization states, state populations, emission intensity and spectrum. In the report the radiance and emission properties of non-equilibrium zirconium plasma is examined and the optimal emission conditions for soft X-ray emission in water window region are explored. Kinetic parameters for non-equilibrium plasma including major inelastic ion interaction processes with non-thermal electrons and radiation, emission and absorption data are obtained in the approach based on Hartree-Fock-Slater (HFS) quantum-statistical model and distorted waves approximation. Modeling of plasma properties and emission is performed by using RMHD Z* code.

Presenting Author

S34

Dual Laser Plasma Photoabsorption Studies Of Gadolinium In The Extreme Ultraviolet Region

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The characteristic extreme ultraviolet (EUV) emission from laser produced plasmas depends critically on the distribution of (highly charged) ion stages and the distribution of excited states within each charge state or ion stage. A key limitation on conversion efficiency (CE) of the incident laser pulse energy into useable EUV radiation, especially for solid targets, arises from the absorption of EUV radiation emitted from the hot laser plasma core by more lowly charged ions in the cooler peripheral regions of the plasma – in summary opacity. This presentation will be focused on computing and measuring the EUV absorption spectra of atoms and lowly charged gadolinium ions. The Gd absorption spectra, obtained using the well established pump-probe technique, 'Dual Laser Plasma Photoabsorption (DLPP)' where one laser plasma acts as the 'sample plasma' while the other constitutes the probing EUV continuum source, will be compared to relativistic time dependent local density approximation calculations to estimate the absolute photoabsorption cross-sections.

Presenting Author

Paddy Hayden is a Postdoctoral Research Fellow in the National Centre for Plasma Science and Technology at Dublin City University. He received his PhD from University College Dublin in 2007 studying atomic and plasma physics processes in plasma based extreme ultraviolet light sources. He was awarded an Irish Research Council for Science, Engineering and Technology postdoctoral research fellowship immediately after receiving his doctorate degree and joined with Professor J. T. Costello's group at DCU. Dr. Hayden also collaborated with many university-based researchers, small enterprises and multinational companies throughout Europe, Asia and the United States. He has co-authored more than 30 scientific journal articles, book chapters, industrial technology transfer reports and patents in the fields of laser-produced plasma applications, laser induced breakdown spectroscopy (LIBS), plasma diagnostics, plasma-facing components and the interaction of intense Free Electron Laser (FEL) extreme ultraviolet light with matter. While maintaining broader research interests, his main focus is currently on the design and implementation of novel extreme ultraviolet light sources as part of a Science Foundation Ireland Investigator Grant (No. 02/IN.1/I99); a collaboration between UCD, DCU and TCD.

S35

Identification of Atomic Resonances for Enhancement of High Harmonic Generation in Laser-produced Plasmas

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In recent years the generation of high harmonic radiation (HHG) in laser produced plasmas has been reported. One of the noteworthy features of this process is the enhancement of harmonics that coincide with resonances in the spectrum of atoms or ions in the plasma [1]. We report on the potential of new, wide resonances in the 40 nm region of a range of elements suitable for the enhanced HHG of the 19^{th} or 21^{st} harmonic of a Ti:Sapphire laser. The laser has a central wavelength of 800 nm, pulse energy of 30 mJ and pulse duration of 30 fs. The resonances were observed using the dual-laser photoabsorption technique using a 1 m normal incidence spectrometer which is sensitive in the 20-200 nm region [2]. Using the Time Dependent Local Density Approximation (TDLDA) the resonance cross sections were calculated for comparison with experimental results. These wavelengths are of interest for surface studies in materials science [3].

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Presenting Author

S36

Electrodeless Z-Pinch^{TM} EUV Source for Next Generation EUV Metrology

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With EUV Lithography systems shipping the requirements for highly reliable EUV sources for mask inspection and resist outgassing are increasing. The sources needed for metrology applications are very different than that needed for lithography, brightness is the key.

In this presentation we will present a unique source technology being reviewed at Energetiq to address the critical source brightness issue. The Electrodeless Z-pinch technology will be shown to be capable of delivering brightness levels sufficient to meet the HVM requirements of AIMS and ABI and potentially API tools. The high brightness EUV plasma is modeled to have a brightness of up to 100 W/mm^2-sr. We will explain the source design concepts, discuss the expected performance and present the modeling results for the new design.

We will also address the need for the next generation source requirements of 6.x nm. We will present results utilizing a higher power electrodeless Z-pinch source to enable research and development of resists and optics at 6.7 nm.

Presenting Author

S37

A Commercial Laboratory Soft-X-ray Source for Water Window Microscopy

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Beginning in 2006, Energetiq Technology Inc. began development [1] of a soft x-ray source based on our commercially successful EUV source [2], based on a unique electrode-less Z-pinch design. Operating in Nitrogen, the source produces up to 400 mW of radiation at 2.88 nm (430 eV) [3]. The source has been used as an illuminator for our own demonstration water-window microscope, and has been successfully integrated by Xradia, Inc. (Pleasanton, CA, USA) with their cryo-tomo-capable soft x-ray microscope, the UltraXRM-S/L220c. While laboratory demonstrations of microscopes driven by table-top x-ray sources have been done [4], this is the first commercially available instrument of this type. We will present detailed performance data for the source.

1. Supported by NIH grants 5R44RR022488-03, 5R44RR023753-03 and 2R44RR022488-04
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4. H. M. Hertz, O. von Hofsten, M. Bertilson, U. Vogt, A. Holmberg, J. Reinspach, D. Martz, M. Selin, A. E. Christakou, J. Jerlström-Hultqvist, and S. Svärd, "Laboratory cryo soft x-ray microscopy," Journal of Structural Biology, vol. 177, no. 2, pp. 267-272, Feb. 2012.

Presenting Author

S38

Spectral Characterization of XUV Sources based on Plasmas Induced by Laser and Capillary Discharge

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We used a free-standing grating spectrometer with 0.01 nm spectral resolution to compare spectral characteristics of two table-top sources of extreme ultraviolet (XUV) radiation - laser-produced plasma from a gas-puff target and plasma produced by pinching capillary discharge. The spectral line at 2.88 nm emitted by nitrogen plasma was of particular interest because it can be used for quasi-monochromatic imaging in the XUV water window. The pulse energy produced by the discharge plasma source at 2.88 nm was found to be about one order higher compared to the laser-plasma source (0.16 mJ $srad^{-1}$ and 0.02 mJ $srad^{-1}$, respectively). On the other hand, the radiation from laser-plasma is more spectrally pure as the spectrum of discharge plasma contains additional weak emission lines of carbon ions generated from the insulating oil.

Presenting Author

Dr. Dalibor Pánek is a Faculty of Biomedical Engineering in the Department of Natural Sciences, Czech Technical University in Prague.

S39

Source Brightness Requirements for EUV Microscopes

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This paper addresses microscopy with plasma based laboratory extreme ultraviolet (EUV) and soft-x-ray sources. The focus is set on the determination of the necessary source parameters like radiance and size from fundamental considerations of the achievable sample resolution, image contrast, detector quantum efficiency and required throughput. Two basic phenomena coming from wave-particle duality of photons are taken into account: the influence of photon noise on signal detection and conservation of light etendue and radiant flux. Two cases are considered in more detailed – resolution optimized bright field microscopy and sensitivity optimized dark field microscopy. Inspection of EUV masks and mask blanks required for EUV lithography at 13.5 nm wavelength is chosen as an illustration for both cases.

Presenting Author

Prof. Dr. rer. nat. Larissa Juschkin received her diploma degree in plasma physics (1995) from the Novosibirsk State University, Russia and Ph.D. (2001) from the Ruhr-University Bochum, Germany. She worked as the R&D head at AIXUV GmbH, Germany (2001 – 2005) on the development of EUV sources and systems for metrology. From 2006 to 2010 she was the EUV Technology group leader at the RWTH Aachen University, Chair for Technology of Optical Systems (RWTH-TOS). In 2011 she joined the Plasma Spectroscopy Group at the University College Dublin and was working on the investigation of short wavelength radiation from laser produced plasmas with an emphasis on atomic processes in highly ionized ions. In 2012 she was called to a professorship for Experimental Physics of Extreme Ultraviolet at the RWTH Aachen University. Her scientific interests and activities are concentrated on plasma based short-wavelength radiation sources and their applications, spectroscopy of highly ionized plasmas, EUV metrology and systems, surface and thin film characterization by spectroscopic reflectometry, EUV microscopy and lithography.

S40

R&D Actinic Blank Inspection Microscope

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One of the most challenging requirements for the next generation EUV lithography at 13.5 nm or even 6.X nm is an extremely low amount of critically sized defects on mask and mask blanks for mass chip production. Fast and reliable defect inspection of such mask blanks is still an open keystone of EUV-technology. We have intensively studied this task experimentally and theoretically within our own feasibility research. We summarize the status of our work as

- Experimental results obtained with the actinic Schwarzschild objective based microscope operating with an EUV-LAMP discharge source from Bruker Advanced Supercon.
- Parameter studies on defect size sensitivity of actinic inspection in dark field mode without resolving the defects.
- Theoretical studies on defect mapping algorithm, tool sensitivity limits and defect detection probability calculations.

We present the concept and the implementation status of the stand-alone R&D ABIT demonstrator.

Funding by the German minster for Science and Education (BMBF) within the project "13 N10572: "EUV mask" in the consortium "EUV Lithographie für den 22 nm Knoten" is appreciated.

Presenting Author

S41

Exploring the Resolution Limit of the Talbot lithography with EUV Light

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Lithography has been in a challenge to bring the resolution down to 10 nm level. Self-imaging Talbot lithography is a promising candidate for the high resolution printing. Utilizing EUV radiation with wavelengths around 11 nm increases the achievable resolution due to the much shorter wavelength in comparison to the conventional UV radiation. However as the size of structures on the mask approaches the wavelength of the radiation, diffraction influence needs to be evaluated precisely to estimate the achievable resolution and quality of the patterns.

Here we present the results of FDTD simulation of the diffraction on EUV transmission masks in dependence on period (pitch) of the mask, with the aim to determine the resolution that can be realistically achieved with the EUV Talbot lithography. Additionally, latest experimental achievements of laboratory-based EUV Talbot lithography will be reported and compared with the results of the numerical simulations.

Presenting Author

S42

XUV Spectroscopy of the Interaction of Laser-produced Plasma with Solid Surfaces

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Processes of interaction of dense, laser produced plasma (LPP) with solid surfaces represent an effective tool for controlled studies of various aspects of plasma-wall interaction, for instance simulating transient events in fusion reactors or EUV light sources and source exposed materials. A wide range of parameters can be explored by changing laser power, target and/or wall material, or target-wall distances. XUV and VUV radiation emitted during this interaction allows the usage of well-established in-situ diagnostics (X-ray and XUV spectroscopy) to quantify and control the interaction.

In the current work, intense XUV radiation was observed during interaction of low temperature LPPs and wall materials [1]. LPPs created on solid targets (CF_2 and Al) by a KrF laser were colliding with a solid wall placed on various distances from the target. The spectral and spatial structure of XUV radiation were studied by means of analyzing XUV spectra of F and Al ions.. At large plasma-wall distances three body recombination was identified as the dominating process responsible for ionic level population and radiation. The experiments demonstrated an effective way to create low temperature (T_e~1-10 eV) plasmas interacting with the solid surfaces and to study the root causes of materials damage.

[1] Kuznetsov A S et al Plasma Phys. Control Fusion 54 (2012) 085019

Presenting Author

S43

High-brightness Liquid-jet Laser-plasma Enabling 10-second-exposure Water-window Cryo Microscopy

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During the last few decades the average and peak spectral brightness of large-scale accelerator-based x-ray sources has increased rapidly, enabling a wealth of novel x-ray methods. In contrast, the brightness of table-top sources has developed slower, limiting the spread of synchrotron-based techniques such as, e.g., water-window x-ray microscopy to a wider scientific community. The soft x-ray source in Stockholm is based on a liquid-nitrogen-jet as regenerative target material, which is excited to a plasma by a high-power pulsed laser. The K_α emission line of the 20 µm plasma produce a narrow-band line at 2.48 nm in the emitted spectrum, where we have achieved a brightness of $>1\times10^{12}$ ph/(s×sr×µm^2×line). To our knowledge this makes it the highest average brightness table-top water-window source. We combine the source with our x-ray microscope and demonstrate high-resolution water-window imaging of cryo-frozen cells with 10-second-range exposure times, comparable to the early synchrotron-based microscopes.

Presenting Author

Mårten Selin got his M.Sc. in Applied Physics at KTH - Royal Institute of Technology in Sweden. He is now a PhD-student in the Biomedical and X-ray Physics group at KTH. His thesis is focused on X-ray optics and X-ray generation with a special emphasis on X-ray microscopy. Currently he is responsible for and taking images of cryo frozen bio-samples with the Stockholm Soft X-ray Microscope.

S44

Research of the CO_2 Laser MOPA System

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Experimental research of a pulse CO_2 laser MOPA system was presented in this report. The laser amplifier is consisted of two CP4000 fast axial flow CO_2 lasers which can produce 4 kW CW laser output each. A mechanical Q-switched CO_2 laser oscillator with a pulse repetition rate of 1-12 kHz and an AO Q-switched low pressure DC discharged wavelength tunable CO_2 laser oscillator with a pulse repetition of 10-70 kHz were made, the pulse duration for both oscillator is about 200 ns. The maximum average power of 1 kW (with nearly TEM00 beam quality) can be obtain in our CO_2 laser MOPA system, while the pulse duration did not change after the amplifier, and the self-oscillation of the MOPA system was not observed. In the future the laser pulse duration will be shortened by the combination of cavity dumping and electro-optical Q-switching.

Presenting Author

S45

Corrosion-resistant, Triple-wavelength Mg/SiC Multilayer Coatings for the 25-80 nm Wavelength Region

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Mg/SiC could be the best reflective multilayer coating in the 25-80 nm wavelength region for applications such as solar physics and tabletop extreme ultraviolet laser sources which are used for plasma studies, materials characterization, photochemistry, nanopatterning, and ultrafast single-shot microscopy. Mg/SiC possesses a unique combination of favorable reflective properties, unmatched by any other candidate multilayer coating in the 25-80 nm region: consistently high reflectance, near-zero film stress, good spectral selectivity and thermal stability up to 350 C. However, Mg/SiC suffers from Mg-related corrosion, an insidious problem which completely degrades reflectance and has prevented Mg/SiC from being used in applications that require long lifetime stability. We have elucidated the origins and mechanisms of corrosion propagation within Mg/SiC multilayers. Based on our findings, we have demonstrated an efficient and simple-to-implement corrosion barrier for Mg/SiC multilayers. The barrier consists of nanometer-scale Mg and Al layers that intermix spontaneously to form a partially amorphous Al-Mg layer and is shown to dramatically reduce atmospheric corrosion while maintaining the unique combination of favorable Mg/SiC reflective properties. We have demonstrated experimentally different concepts for corrosion-resistant Mg/SiC multilayers which achieve high reflectance in up to three narrow bands simultaneously, in the 25-80 nm region.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Presenting Author

Regina Soufli received her Ph.D. in Electrical Engineering from the University of California, Berkeley, and was staff scientist at the Harvard-Smithsonian Center for Astrophysics working for NASA's Chandra X-ray Observatory. At Lawrence Livermore National Lab she has been principal investigator on EUV/x-ray optics programs for EUV lithography, solar physics, synchrotron and free-electron lasers, and high-energy physics. She has recently been working on x-ray optics for the Linac Coherent Light Source (LCLS), the world's first x-ray free electron laser, and on EUV multilayer optics for NASA/NOAA's space weather satellites and NASA's Solar Dynamics Observatory. Her interests are in EUV/x-ray interactions with matter, surface science, thin films, roughness and scattering. She is author of over 60 publications and a book chapter, and has received two "R&D 100" awards.

S46

XUV and EUV Applications with EUV Sources for Metrology

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EUV sources for metrology are a keystone for the infrastructure of EUVL. Within Bruker ASC and with our research partners we are investigating and producing discharge and laser produced sources since 1996, such that we can provide and engineer matched solutions for many tasks.

With the discharge based EUV-source for metrology – our EUV-Lamp – first shipped in 2001 we meanwhile have produced about 20 systems. The typical EUV-Lamp delivers up to 750 mW/(2 π sr) of in-band EUV (> 8 W/(2 π sr) of total EUV). About 500 M pulses of electrode life supports up to one year of 8 hour per day emission. At our partner Fraunhofer Institute for Lasertechnics, prototype sources based on similar platform are delivering up to 40 W/(2 π sr) of in-band EUV; with brightness of up > 20 W/mm²/sr. When source brightness is the issue, laser produced (LPP) sources are advantageous. Members of our group are working since 1997 on and with LPP EUV sources.

Most of the EUV-Lamps, which we have produced are specially interfaced or directly integrated into tool solutions. The lamps have been and are being used in EUV-Reflectometers, EUV resist exposures, EUV and x-ray microscopes, EUV-scatterometer, EUV- Interference Lithography, in source metrology calibration, for optics qualification and as sources for spectrograph calibration in fusion and solar physics. LPP sources are used in our spectrophotometer (CEUVS) and in x-ray microscopes. Research and use of EUV-LPP sources is ongoing at our research partners at RAC, Remagen, LZH, Hannover, MBI Berlin and FhG-ILT, Aachen.

Based on these sources and with our proprietary polychromatic reflectometry, we have realized tools, which fulfill such high demands together with fast measurement times. Typically, for characterization of one small spot on a sample of << 0.1 mm² in size, exposure times – depending on spectral resolution - of 5 – 20 seconds are sufficient, which allow to characterize > 180 spots per hour or > 3 samples per hour with > 30 spots on each sample. This has been demonstrated at our actinic EUV mask and mask blank reflectometer (EUV-MBR) and in flexible EUV characterization of normal and grazing incidence and foil and gas transmission with our new EUV-Spectrophotometer CEUVS.

With tailoring source features, solutions like actinic defect inspection (EUV-ABIT), EUV interference lithography and critical dimension scatterometry, optics scatterometry and research in fusion and solar physics have been demonstrated.

Support by the German minster for Science and Education (BMBF) within the project “13 N10572: “EUV mask” in the consortium “EUV Lithographie für den 22nm Knoten” is appreciated.Some of the work is from collaborations with RWTH Aachen, RAC Remagen, Fraunhofer Institute for Lasertechnics, Aachen and MBI Berlin.

Presenting Author

S47

Next Generation of EUV Lithography: Challenges and Opportunities

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Reduction of light wavelength used in Litho tools has enabled shrink of printed feature. Current immersion systems based on 193 nm are printing features as small as 32 nm. State of the art EUV lithography has already demonstrated excellent capability to print 18 nm features in single exposure and is expected to enable printing of <16 nm features.

Shrinking wavelength with maintaining or increasing throughput is a traditional way to enable improved imaging for the last 20 years. Transition from 13.5 nm to a shorter wavelength offers a possibility to combine high imaging capabilities with still managing process window. Change of working wavelength will introduce changes to a number of subsystems of the lithographer including source and optics.

Our work is aiming at investigation of the potential of a number of shorter wavelength candidates $\lambda<13.5$ nm. Here we review requirements that these systems should meet to enable continuation of lithography roadmap below 7 nm. Specifications of the key system elements including source, optics, resist are discussed.

Presenting Author

Dr. Andrei M. Yakunin is currently project leader at ASML Research. He has worked for ASML since 2007 with the primary focus on EUV sources. He obtained his master degree in applied physics and mathematics from Moscow Institute of Physics and Technology in 2001. He received his PhD C*um Laude* in 2005 from Eindhoven University of Technology, The Netherlands (TU/e). The subject of his PhD work was the study of magnetic impurities in III-V semiconductors at nano-scale. From 2005-2007 he did his postdoctoral work at TU/e in the field of semiconductor spectroscopy and single photon emission. He has over 15 publications and over 20 patens. He is also the winner of ASML patent award.

S48

Erasmus Mundus Joint Doctorate Programme EXTATIC (*EUV and X-Ray Training in Advanced Technologies for Interdisciplinary Cooperation*) - Program Review

Paul van Kampen

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The Erasmus Mundus Joint Doctorate programme EXTATIC (*EUV and X-Ray Training in Advanced Technologies for Interdisciplinary Cooperation*) offers a postgraduate education program in extreme ultraviolet (EUV) and X-ray science to a new generation of high achieving graduate students. It provides the transferable skills necessary for thriving careers in a growing domain that underpins innovative technological development across a diverse range of disciplines in the 'nanotechnology waveband' such as EUV Lithography and X-ray microscopy in the 'water window'. EXTATIC provides a combination of 'hands-on' research training, industrial placements, courses and workshops on scientific and complementary transferable skills. This talk is an overview of the EXTATIC program and the projects that have just commenced under the 2012 edition.

Presenting Author

Paul van Kampen is a Senior Lecturer at the School of Physical Sciences at Dublin City University, and a member of the Centre for the Advancement of Science and Mathematics Teaching and Learning (CASTeL) and the National Centre for Plasma Science and Technology (NCPST). He obtained a Ph.D. in Experimental Physics (EUV Photoabsorption in Atoms and Ions) from University College Dublin. Paul teaches physics and physics education at undergraduate and postgraduate level, and is heavily involved in science teacher education. He has been Academic Director of the EXTATIC EMJD program since September 2011. Paul is married to Lorraine with two daughters, Maria and Amy.

S49

EUVL - A Reality in the Making
The Reality of Laser Assisted Discharge Plasma EUV Light Sources

Jeroen Jonkers

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Scalable in power and delivering highly repeatable and stable output at 13.5 nm, XTREME technologies GmbH's Laser produced Discharge Plasma (LDP) technology is maturing fast and now proven a viable solution to generate the EUV photons that will power next generation lithography EUV exposure tool.

After demonstrating experimentally the long term scalability of LDP, the most recent performance of integrated sources in the Lab and in the Fab will be discussed. The challenges and improvements in the demonstrated usable output will be detailed.
However, because high throughput without stability would be tantamount to printing defective semiconductor devices merely at high speed, to increase EUV power without compromising dose stability is critical. LDP dose stability technology will be outlined and performance data provided.

Alongside, the success of EUV in an HVM environment will require high availability and reliability. The status of current LDP sources operated 7x24 will be reported. Highlighting the development status of the different modules, the current technological path of LDP towards HVM will then be summarized.

Presenting Author

Jeroen Jonkers received his PhD in Plasma Physics at the Eindhoven University of Technology (Eindhoven, The Netherlands) in 1998. He then joined Philips Research in Eindhoven, The Netherlands. From 2001 to 2009, Dr. Jonkers worked at Philips Extreme EUV GmbH as Senior Scientist and Program Manager. He is currently Product Architect at Xtreme technologies GmbH.

S50

Multilayers for 6.8 nm Wavelength

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Lithography based on the wavelength of 6.x nm is considered to be a potential extension of the current 13.5 nm EUV lithography. Light sources might be based on Tb or Gd. The published spectra of plasmas created from these materials show highest intensities at 6.5 and 6.8 nm respectively. Multilayer mirrors (MLMs) based on La and B show the highest optical contrast for the 6.6-7 nm wavelength range and a maximum reflectance at 6.64 nm, where the B absorption is minimal. It is not possible to design high reflective B-based mirrors for 6.5 nm because this would be below the B-K absorption edge. In theory the reflectivity of La/B MLMs at 6.8 nm is only a few percent lower than at the optimal wavelength of 6.64 nm, but measurements of real multilayer mirrors show a significantly larger reduction of reflectivity at 6.8 nm. The origin of this larger drop is the reduced optical contrast of the deposited La/B mirror with respect to theoretical case. In the presentation we will discuss how the multilayer structure influences its reflectivity profile and the ways to optimize La/B mirrors for 6.8 nm.

Presenting Author

Eric Louis is a senior scientist at FOM Rijnhuizen (the Netherlands) where he is involved in research and development of soft X-ray and EUV multilayer reflective coatings since 1992. He worked on multilayers for several applications such as space research and synchrotron beam lines, but focused his research primarily on multilayers for EUV lithography. As leader of the group 'Advanced applications of XUV Optics', Eric Louis has been responsible for research, development and coating of various optics for EUV lithography.
The extensive know how developed for this application is the basis for the development of multilayer coated optics for XUV and soft X-ray free electron lasers.

S51

EUV Source For Metrology of EUV Masks *(Tentative title)*

Heiko Feldmann

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The introduction of EUV lithography with its huge jump in wavelength and resolution is extremely attractive for semiconductor manufacturing. Large investments from key players of the industry are now taking place in order to move EUV to the chip fab. EUV sources are a key element for this new infrastructure, not only for lithography itself but also for metrology and qualification of all components participating in EUV imaging.

The talk focuses on sources for metrology of lithographic masks. Mask metrology tools supporting mass production of semiconductors need to have high throughput, high precision and high reliability. All this has direct influence on the light sources that can be employed. For defect review, where the need for actinic optics is most obvious within the mask industry, a first generation of AIMS(TM) EUV systems is now being built. With the further development of EUV, requirements on AIMS will increase, and this leads to more challenging demands for its light source.

Presenting Author

Heiko Feldmann works as Principal Scientist for Carl Zeiss SMT GmbH. After graduating with a PhD in Theoretical Physics from Würzburg University. He first started as an optical designer with Carl Zeiss. His focus now is on system concepts and technology roadmap. One of his recent projects was the concept layout of the metrology core of AIMS(TM) EUV.

S52

Modeling and Optimization of Pre-conditioned LPP targets

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An integrated model is developed to describe the hydrodynamics, atomic, and radiation processes that take place in EUV sources based on laser-produced plasma with an advanced tin targets. The modeling was performed by using the RZLINE code — a numerical code for the simulation of EUV emission by hot dense plasmas. The purpose of the simulation is to evaluate the spectral characteristics of the radiation source, conversion efficiency, source size, evaporation rate of the target, energetic, and space distribution of debris (nanoparticles, neutrals, and ions). The optimization of different type of targets is fulfilled.

Presenting Author

Konstantin N. Koshelev is the president of RnD-ISAN and a leading scientific specialist in plasma physics and atomic spectroscopy. He was invited professor at Pierre and Marie Curie University (1991), Orsay University (1992) and Auburn University (1990 and 1995).

S53

Modeling of Absorption and Scattering of IR laser Radiation by LPP Targets

A. S. Grushin[1,2], I. P. Tsygvintsev[1,2], V. G. Novikov[1,2], V. V. Ivanov[1,3]

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A mathematical model and algorithm for simulation of laser radiation absorption with accounting refraction and reflection by target plasma in the geometrical optics approximation is presented. An analytical solution of the differential equations assuming a constant gradient of the square of optical coefficient in the cell is proposed. A numerical calculation algorithm is developed, and estimation of its convergence has been done. For a partial accounting of effects that are beyond the geometrical optics approximation, one-dimensional model of the layered medium was used.

Presenting Author

S54

Modeling of Plasma Dynamics and EUV Generation for Distributed Sn Targets Irradiated with Short Laser Pulses

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Generation efficiency of EUV radiation by laser-produced plasma (LPP) sources is defined by the effective coupling of the laser radiation to Sn target. Expected that usage of the distributed targets (DT) consisting of a number of small (from one to few micrometers) droplets distributed over the volume with a total size of a few hundred micrometers allows noticeably increase laser radiation absorption and in-band conversion efficiency.

To simulate optical, atomic and hydrodynamic processes in LPP sources based on DT approach, an integrated model is being developed. The hydrodynamic plasma model includes diffusion-like radiation transport with 100 and more groups of spectral groups with well represented in-band EUV. Non-stationary ionization (recombination) processes are also included. Energy fluxes to and from a target surface are taken into account: electron and ion thermo-conductivity, radiative transfer in every spectral group, condensation and recombination of vapor and plasma. Verified atomic data are used for calculation opacity and emissivity. Results of a numerical simulation are presented for various types of DT.

Presenting Author

S55

Optics for EUV/XUV/XR Sources and Laboratory Submicron Microscopy

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S56

Unresolved Transition Arrays and their role in EUV and Soft X-ray Source Development

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Unresolved transition arrays (UTA) appear frequently in the extreme ultraviolet (EUV) and and soft x-ray spectra of medium and high Z-elements. They broadly fall into two types, $\Delta n = 0$ arrays, where emission from adjacent ion stages overlap in energy and whose intensity is very sensitive to plasma ion density and $\Delta n = 1$ transitions where emission moves to shorter wavelengths in successive ion stages thereby reducing the radiation transport problem. Because of their inherent brightness the former are used or have been proposed as sources for EUV lithography or as broad-band water window sources. $\Delta n = 0$ arrays are broad at intermediate Z values (such as Sn, Z=50) decrease in width because of configuration interaction and orbital contraction effects up to Z= 60 or so and thereafter broaden again reflecting the effects of spin orbit splitting on the configurations involved. Because of their Z scaling, use at shorter wavelengths requires higher temperature plasmas and recent work has shown that $\Delta n = 1$ arrays may provide useful sources at shorter wavelength at lower electron temperatures, especially if used with mirrors of limited reflection bandwidth. We have also found that dielectronic recombination and satellite emission can also enhance the emission in these arrays.

Presenting Author

Prof. Gerry O'Sullivan obtained his PhD from University College Dublin (UCD) in 1980 for work on the spectroscopy of laser produced plasmas of medium to high Z elements that included the first observation the unresolved arrays now studied as emission sources for EUVL at 13.5 and 6.x nm, changes in their EUV emission due to opacity and the application of higher Z plasmas as sources of EUV continuum radiation. After a brief period at the University of Maryland and National Bureau of Standards he returned to Dublin where he was employed at Dublin City University from 1981 before moving to a lectureship at UCD in 1986. He is currently a Professor at UCD and served as Head of the School of Physics from 2002 - 2008. His research interests include EUV and soft x-ray continuum generation from laser produced plasmas and application to inner shell photoabsorption studies of atoms, ions and molecules, investigation of unresolved transition arrays (UTA) and their application as high brightness EUV sources, determination of the electronic structure of medium and high Z ions and spatial and temporal characterisation of laser produced plasmas.

In recent years, aided primarily by funding from Science Foundation Ireland, this work has focussed strongly on studies relevant to the development of EUVL sources. He has published more than 110 papers and is a member of the editorial board of European Journal of Physics. He is a member of the Royal Irish Academy and a Fellow of the Institute of Physics.

S57

New High Reflective Multilayer Designs for the EUV and Soft X-ray Range

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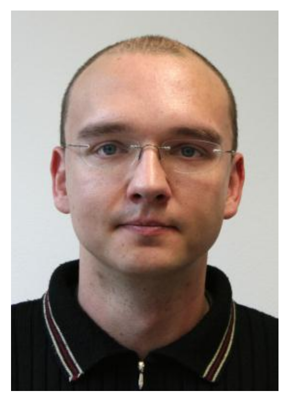
EUV Lithography is the most promising method enabling semiconductor scaling to resolutions of 22 nm and below. Due to the absorption in the EUV spectral range, EUV optics such as collector, illumination and projection optics, have to be coated with a highly reflective multilayer coating in order to achieve the required peak reflectance of close to 70 %.

But the more EUV Lithography is pushed to high volume manufacturing, the higher is also the demand on optics for very special measurement application in these wavelengths.

The Fraunhofer IOF possesses extensive knowledge of the optical, mechanical and chemical properties of substrate and layer materials as well as corresponding design software and coating machines.

This paper provides a review of individually designed, refined and optimized multilayer coatings for broadband mirrors, beam splitters and polarizers in the EUV and soft X-ray range. Latest coating results will be presented.

Presenting Author



Marco Perske received a Dipl.-Ing. degree in 2006 and M.Eng. degree in 2009 both at the University of Applied Science Jena. Since 2007 he works at the Fraunhofer – Institute for Applied Optics and Precision Engineering as scientist and process engineer with main focus on EUV and X-ray optics.

S58

Discharge based EUV Source for Metrology

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The current status and the scaling potential for the brilliance of the Hollow Cathode triggered pinch plasma (HCT) are presented. Such sources are already in commercial use for the technology development of EUV lithography, e.g., for mirror contamination studies, mask blank inspection or resist development. For future Aerial Imaging Microscopy (AIMS) of EUV masks special care has to be devoted to the brilliance scaling in order to guarantee a sufficient throughput. With the recent state of development already more than 20 W/(mm^2 sr 2% b.w.) at a central wavelength of 13.5 nm could be demonstrated. This is close to the specification for a future AIMS tool. Based on experimental data, the roadmap for achieving more than 35 W/(mm^2 sr) and the maximum achievable brilliance for the concept under consideration will be discussed.

Presenting Author

Klaus Bergmann received his PhD degree from the Faculty for Engineering, RWTH Aachen University, in 1996 in the field of discharge based soft x-ray sources. Since 1992, he has been with the Department for Plasma Technology at the Fraunhofer Institute for Laser Technology. Currently, he is Group Leader for the development of radiation sources for semiconductor lithography.

S59

Nanoscale Multilayer Membranes as Optical Elements for EUVL

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Transparent optical elements for EUV could have several critical applications, ranging from spectral filters to particle protection (e.g., pellicle for reticles). Since practically no material is transparent to EUV, the only known solution is to make the optical element extremely thin (<100nm). This results in enormous challenges in manufacturing (e.g., making the membrane free-standing) and in meeting the requirements on heat load, mechanical strength, EUV transmission, etc.

In this paper we present recent developments on free-standing multilayer membranes, fabricated and studied as EUV transparent elements for lithography tools.
Membranes 53 ÷ 40 nm-thick, and as large as 160mm, have been fabricated. They provide inband transmission up to 74-76% and are considered as potential spectral purity filters (SPFs) to suppress DUV and 10,6 □m radiation with coefficients $10^2 \div 10^3$. SPF membranes were tested to withstand prolonged heating at 950°C and repetitive deformations under modulated power load.

Stopping fast debris particles as valuable additional functionality of SPF membranes has been studied with an LPP source and a particle velocity filter. It was found that membranes are not punched through by metal particles with sub-micron dimensions and velocities up to 1000 m/s. Development of super-thin membranes as pellicles, targeting a two-pass inband transmission above 80% is in progress. Currently a one-pass transmission of 86% has been demonstrated with 25 nm membranes on 80 mm aperture frames. The samples sustained absorbed power loads above 1 W/cm^2 with < 0.1 mm deviations from the initial quasi-stretched surface shape and in-plane acceleration of at least 15g. Achievement of higher inband transmission along with solving specific application issues is planned for this year.

Presenting Author

S60

EUV Spectra of Highly Charged Heavy Ions in the NIST EBIT

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Measurements of extreme ultraviolet (EUV) radiation from highly-charged heavy ions were made at the National Institute of Standards and Technology (NIST). The ions were generated and confined in an electron beam ion trap (EBIT) and the spectra were recorded with a flat-field grazing-incidence spectrometer in the wavelength range 3-17 nm. The EBIT was operated at beam energies that optimized the production of Rb-like to Cu-like Gd ions. Strong (N-shell) n=4 – n=4 transitions were identified with the collisional-radiative (CR) modeling code NOMAD [1]. EUV spectra of Gd, Dy and W are dominated by the presence of narrow unresolved transition arrays (UTAs) [2].

These arise from interactions between $4p^64d^{N-1}4f$ and $4p^54d^{N+1}$ configurations and overlap in adjacent ion stages. This work enhances other studies of n=4 to n=4 EUV transitions carried out at NIST on tungsten [3], hafnium, tantalum and gold [4] and can be used for diagnostics of hot plasmas in fusion devices and for studies of trends in atomic structure. The gadolinium data will aid recent research efforts on next-generation lithographic sources at shorter wavelengths [5].

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Presenting Author

S61

New Type of DPP Source with Liquid Tin Jets Electrode - Recent Progress

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A new approach for discharge-produced plasma (DPP) extreme ultraviolet (EUV) sources based on the usage of two liquid Sn jets as discharge electrodes has been developed and is tested.[1] Discharge was ignited using Nd-YAG laser ablation of one (or both) of jets. Spectral, time and energy characteristics of EUV radiation are similar to conventional DPP schemes with rotating wheels. Modeling and experiments demonstrate that due to high velocity of the jets the proposed scheme of EUV source able to dissipate up to 200 kW of electrical power without overheating the nozzles and tin surface.

New EUV source with projected repetition rate up to 8 kHz and dissipated electrical power up to 32 kW in continuous mode and 40 kW in burst mode has been designed and constructed. The power limitation is imposed by parameters of existing discharge excitation circuit. The Sn jets with up to 2 mm diameters were circulating in a closed loop by means of centrifugal pump with magnetic coupling. In first experiments with repetition rates 100 Hz conversion “in band” efficiency (CE) more than 2% in 2π sr was shown. It was found that the introduced electrode configuration allows the channeling of essential parts of debris plasma in directions opposite to the EUV collector.

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Presenting Author

S62

Tin LPP Source Modeling for EUVL at 13.5 nm

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An unresolved transition array (UTA) can be the strongest feature in EUV LPP spectra, consisting of thousands of transitions between bands of near-degenerate energy levels [1]. The complexity of the configurations is such that a line-by-line analysis is computationally extremely intensive and statistical methods can be used to characterise a UTA by position ($\mu 1$) and width (σ).

To estimate emission in a 2% bandwidth centred on 13.5 nm, the weighted oscillator strength (*gf*) versus wavelength (λ) is calculated using a Hartree-Fock configuration interaction code [2] for 4d-4f, 4p-4d and 4d-5p transitions. The number of transitions of some ions exceeds 100,000 lines.

Because of the large number of transitions and complexity of the UTA, as well as the computationally intensive nature of radiation transport calculations, statistical methods can be used to estimate the spectral profile [3]. UTA width can overestimate by a factor of approximately 2 because of "outliers". Statistical/convolved LSQ match gives a better fit (*e.g.* Sn XI 0.55$\rightarrow$0.20 nm) [4].

Increasing laser power density shows increased in-band UTA brightness [5]. Emission increases and decreases with increased laser intensity (or electron temperature) as the UTA ions move in- and out-of-band, as in the steady-state CR model [6], where an average temperature and density is assumed over the whole plasma. Wavelength at peak emission also decreases as power density increases as seen in the time-dependant model.

The impact of wavelength λ and power density ϕ on ion distribution and electron temperature is calculated for a Nd:YAG (λ = 1064 and 355 nm) and CO_2 (λ = 10600 nm) laser. The laser power densities, ϕ, are chosen to keep $\lambda^2\phi$ constant, thus keeping the electron temperature constant in the CR rate equations [6]. (The 355-nm laser is included to highlight the emission dependence on electron density, primarily three-body recombination, and gives greatly reduced Sn^{10+} and Sn^{11+} ions, the main emitters at 13.5 nm.) The figure of merit shows an increase for the CO_2 laser, where the in-band Σgf is 13.4% greater at 32 eV and 2.7% greater at 36 eV [7].

The influence of reduced electron density in the CO_2 LPP (~ 1/100, where $n_e \propto 1/\lambda^2$) is considered in a 1-D radiation transport model. Plasma opacity is less in the lower electron density CO_2 plasma, resulting in less absorption and a brighter source. A more than 2-fold increase in conversion efficiency is predicted for the CO_2 laser over that attainable with the Nd:YAG [7], close to the experimentally observed values [8,9].

The 2-D RMHD code Z* [10] models emission in an optically thick tin LPP. The implicit Eulerian-Lagrangian code solves MHD, ionization kinetics with radiation transport and uses an average atom model to account for all possible states and transitions.

Optimum 4d-4f + 4p-4d in-band emission occurs primarily from the plasma core at an electron temperature of 30-40 eV [11,12]. However the core emission is reduced by self-absorption and absorption in the colder wings because of the high absorption cross section of lower stage ions [13].

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